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ALPHABETICAL LIST BY AUTHOR'S NAME

BEIN, SELWYN: The relationship of total phosphorus concentration in sea water to Red Tide blooms. (No. 4, Dec., 1957)	316
BSHARAH, LEWIS: Plankton of the Florida Current V. Environmental conditions, standing crop, seasonal and diurnal changes at a station forty miles east of Miami. (No. 3, Sept., 1957)	201
DE SYLVA, DONALD P.: Studies on the age and growth of the Atlantic sailfish, <i>Istiophorus americanus</i> (Cuvier), using length-frequency curves. (No. 1, March, 1957)	1
GIBBS, ROBERT H., JR.: Preliminary analysis of the distribution of white marlin, <i>Makaira albida</i> (Poey), in the Gulf of Mexico. (No. 4, Dec., 1957)	360
HELA, ILMO, CLARENCE A. CARPENTER, JR., AND J. KNEELAND McNULTY: Hydrography of a positive, shallow, tidal bar-built estuary (report on the hydrography of the polluted area of Biscayne Bay). (No. 1, March, 1957)	47
HULBURT, EDWARD M.: Sea-level fluctuations at Charleston, South Carolina. (No. 1, March, 1957)	21
JOHNSON, T. W., JR. AND SAMUEL P. MEYERS: Literature on halophilous and halolimnic fungi. (No. 4, Dec., 1957)	330
MENZIES, ROBERT JAMES: The marine borer family Limnoriidae (Crustacea, Isopoda). (No. 2, June, 1957)	101
MOORE, H. B. AND D. L. O'BERRY: Plankton of the Florida Current IV. Factors influencing the vertical distribution of some common copepods. (No. 4, Dec., 1957)	297
OWEN, H. MALCOLM: Etiological studies on oyster mortality II. <i>Polydora websteri</i> Hartman (Polychaeta: Spionidae). (No. 1, March, 1957)	35
ROBINS, C. RICHARD: Effects of storms on the shallow-water fish fauna of Southern Florida with new records of fishes from Florida. (No. 3, Sept., 1957)	266
SCHAFER, R. D. AND CHARLES E. LANE: Some preliminary observations bearing on the nutrition of <i>Limnoria</i> . (No. 4, Dec., 1957)	289
SPARKS, ALBERT K.: Some digenetic trematodes of marine fishes of the Bahama Islands. (No. 3, Sept., 1957)	255
STOMMEL, HENRY: Florida Straits transports, 1952-1956. (No. 3, Sept., 1957)	252
VOSS, GILBERT L.: Observations on <i>Ornithoteuthis antillarum</i> Adam, 1957, an ommastrephid squid from the West Indies. (No. 4, Dec., 1957)	370
Regional Bibliography for 1956. (No. 3, Sept., 1957)	276

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BULLETIN OF MARINE SCIENCE OF THE GULF AND CARIBBEAN

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NUMBER 1

STUDIES ON THE AGE AND GROWTH OF THE ATLANTIC SAILFISH, *ISTIOPHORUS* *AMERICANUS* (CUVIER), USING LENGTH-FREQUENCY CURVES¹

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The Marine Laboratory, University of Miami

ABSTRACT

Length frequencies of 8630 young to adult Atlantic sailfish, *Istiophorus americanus*, from southern Florida, the western Bahamas and the Gulf of Mexico were plotted by month for a three-year period. Growth is rapid during the apparently short life span, and fish hatched in June appear to reach a modal value of about 56 inches total length by November, at which time they weigh about seven pounds. At one year they have increased to 72 inches and an average weight of 21 pounds. By their second summer they are about 85 inches long and weigh about 43 pounds. The length increment drops off rapidly, and by their third year sailfish are about 92 inches long, with an average weight of 63 pounds. Interpretation beyond this point is difficult, but apparently few fish reach four years of age. There is great variation in weight for a given unit of length, particularly in the longer specimens. A 92-inch fish may weigh from 42 to 109 pounds, with an average weight of 63 pounds. An apparently high natural mortality in this species is reflected in the occurrence of only two major year classes in the sport fishery during any one month. During the winter months nearly half of the sport fishery is composed of six-month old fish. The conservation value of a Florida law that now prohibits the possession of more than two sailfish is questioned. It is suggested that tagging experiments now in progress be intensified during the winter months and that these be confined largely to the smaller specimens.

INTRODUCTION

The Atlantic sailfish, *Istiophorus americanus* (Cuvier), is well known as a sport fish in the southern Florida area. Since 1948 the University of Miami Marine Laboratory has been engaged in a study of the biology of this species, and since a knowledge of age and growth

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is essential to the rational management of any species, attempts were made, by tagging, to determine age, growth and migratory pattern.

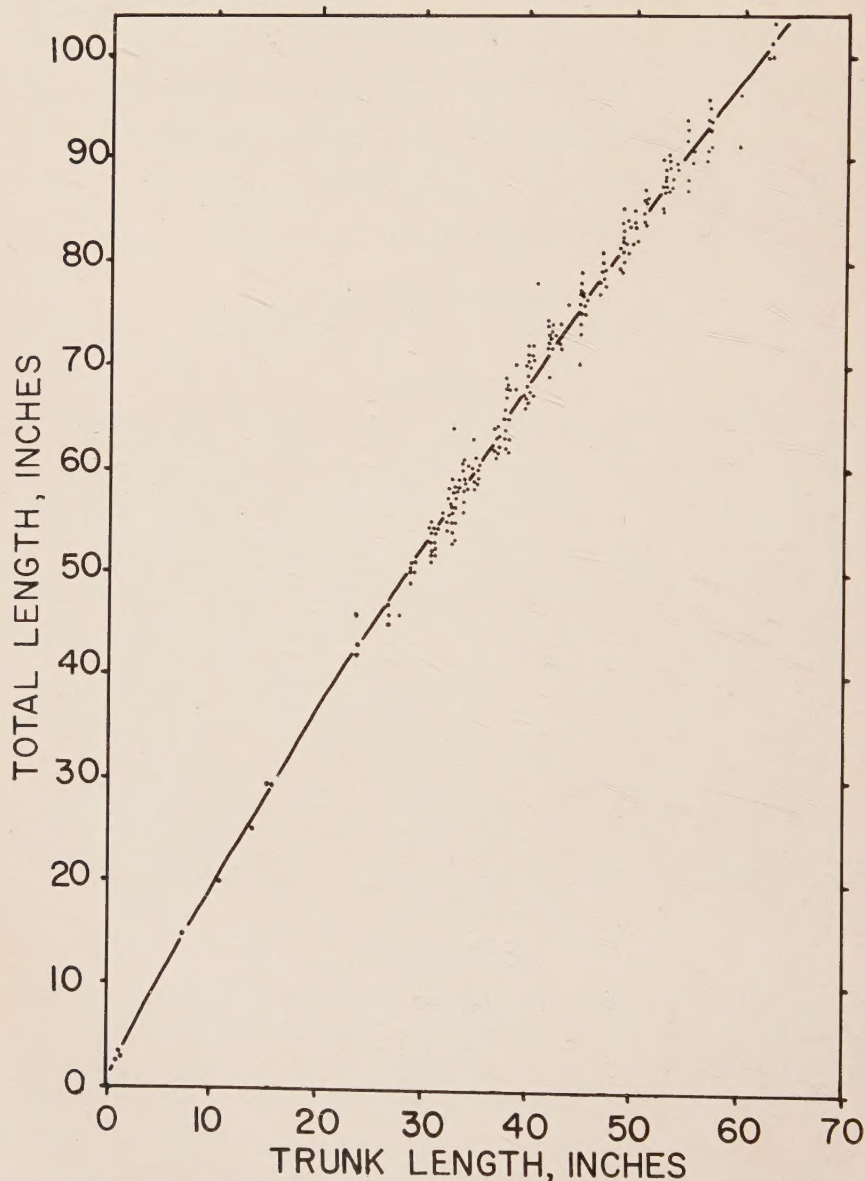


FIGURE 1. Relationship between total length and trunk length for 223 specimens of the Atlantic sailfish, *Istiophorus americanus* (Cuvier), both male and female.

Due to the very low rate of tag recovery to date (5 returns out of 2,032 releases) little information has been obtained from this source. The method used here has yielded valuable data but needs to be checked by conventional analyses of annular marks.

The use of length-frequencies in assessing age and growth has been described by Petersen (1893). This method utilizes lengths or weights of a large number of fish which encompass the size range for the species. When plotted by successive months these lengths theoretically will fall into multi-modal frequency distributions, the modes of which signify the most common size of each age group represented, and therefore presumably there will be a frequency polygon for each age group. This requirement seldom is satisfied in practice because for older age groups growth rate decreases and the frequency polygons become so close together as to make visual analysis difficult or impossible. For such cases Cassie (1954) has described a method by which frequency polygons of large samples can be dissected by the use of probability analysis paper.

METHODS AND MATERIALS

Through the kind cooperation of Mr. Al Pflueger, Miami taxidermist, the lengths of a large series of adult sailfish were made available to the author. *Total length* of the fresh specimens was taken by Mr. Pflueger and his assistant, measuring from the tip of the upper jaw, or "bill," with the mouth closed, to a vertical line drawn between the tips of the caudal lobes. A second measurement, here termed "*trunk length*," was taken from the posterior edge of the orbit to the anterior insertion of the caudal keels; this was used for the length-frequency diagrams because data from specimens with broken bills or tails could still be utilized. Correlation between them is quite high (Fig. 1), though slightly curvilinear, despite the numbers of broken or malformed bills indicated in Mr. Pflueger's records. These aberrant individuals show up on the scattergram as being somewhat removed from the regression slope. This slope was fitted by eye, as are all other slopes presented in this paper, and both lengths are presented subsequently in the length-frequency diagrams.

At first it was planned to convert lengths to weights and thus present weight-frequency diagrams for sailfish as was done for bigeye tuna, *Thunnus sibi*, by Iversen (1955), but due to the large variation in the weight-length relationship of the sailfish, as evidenced by the scatter of points about the regression slope (Fig. 2) which would

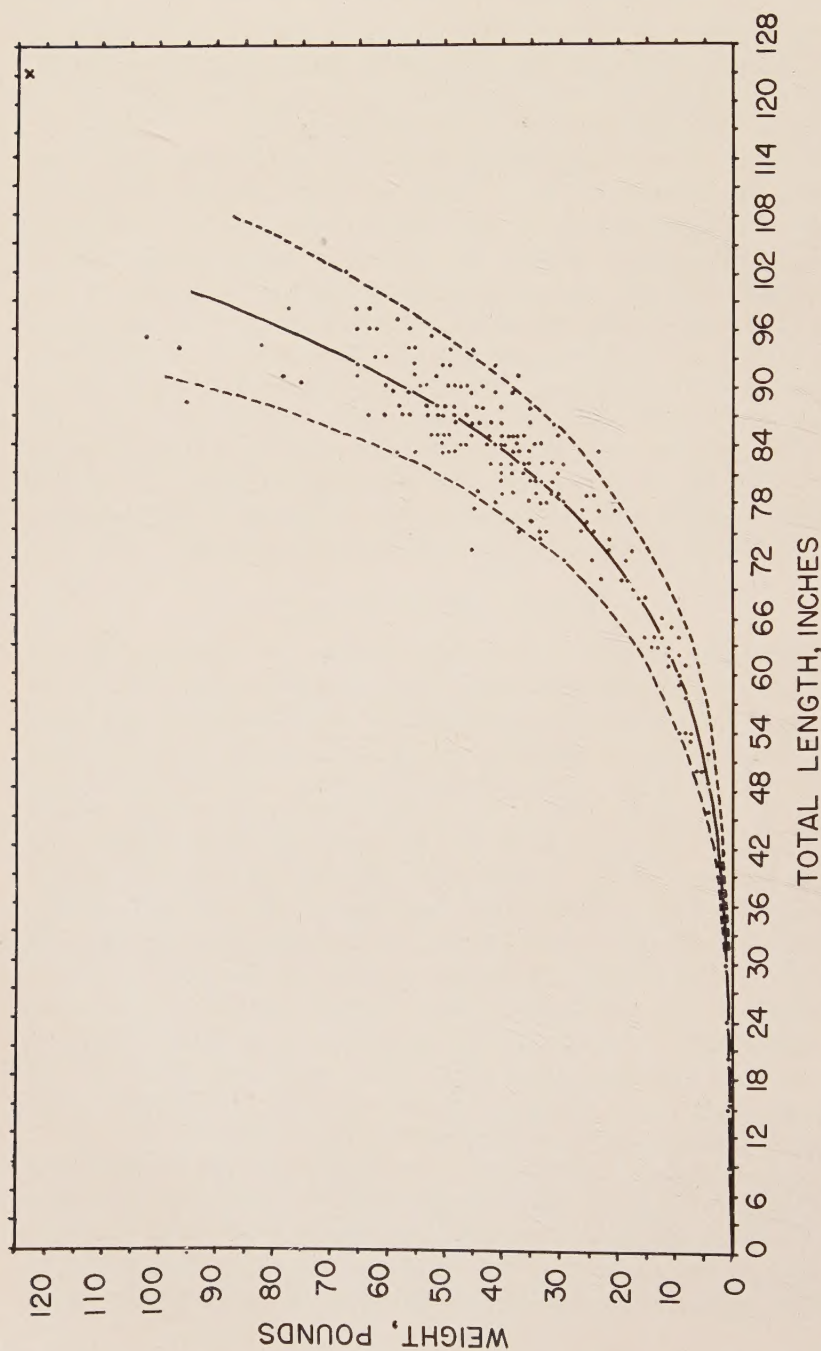


FIGURE 2. Length-weight relationship for 189 male and female Atlantic sailfish. Center line indicates average weight at a given length; dashed lines indicate roughly the range of variation to be expected. Data collected by Marine Laboratory staff, 1948-1956. Cross indicates world record Atlantic sailfish.

cause great overlap between year classes if weights were used, it was decided that length-frequencies would better depict the growth.

ACKNOWLEDGMENTS

In addition to the large number of young and adult sailfish data received from Mr. Pflueger, a number of specimens and measurements were donated by the following persons, to whom the author wishes to express his appreciation: Edgar L. Arnold, Jr., Frank J. Mather III, Joseph T. Reese, Luis R. Rivas, and Durbin C. Tabb. Thanks are also due to Douglas Faulkner and James D. Regan for assistance with the tabulation of the data, and to Anita Feinstein, Edwin S. Iversen, Edward C. Raney, C. Richard Robins, F. G. Walton Smith, and Gilbert L. Voss for their valuable suggestions and criticisms. Gratitude is due to Mr. Charles F. Johnson for financial support and to the National Geographic Society fish larvae program for the loan of material.

GROWTH OF YOUNG

Data on the location, time of capture and length of young sailfish are presented in Table 1. All are from southern Florida, the western Bahamas and the Gulf of Mexico, with the exception of one specimen from Haiti.

The growth rate of young sailfish is rather difficult to determine accurately because of the extended spawning period, the probable differential spawning time of different populations, and the small numbers of young available for study. However, it is felt that some tentative conclusions can be drawn, but this material must be regarded as incomplete.

It is seen in Figure 3 that the very young appear over a long period from late April until mid-August. Mr. Pflueger informs me (personal communication) that he has found ripe females as late as October, so it is likely that some spawning occurs in the fall. While there is considerable scatter in the graph, it is felt that a slope which depicts the probable *average* growth rate is tentatively justified. It would appear that sailfish average a total length of seven inches at the end of their first month of life, 20 inches by their second month, 35 inches by the third month, and about 44 inches by their fourth month. Undoubtedly there is variation here between early- and late-spawned fish, as the former may have a greater supply of food available to them than those spawned later in the summer when planktonic food is less

abundant. Also the growth rate probably varies to some extent between populations, and since the grouped data presented here represent material from several rather widely separated areas, possible differences in growth rates from these regions may account for some of the variation observed in Figure 3.

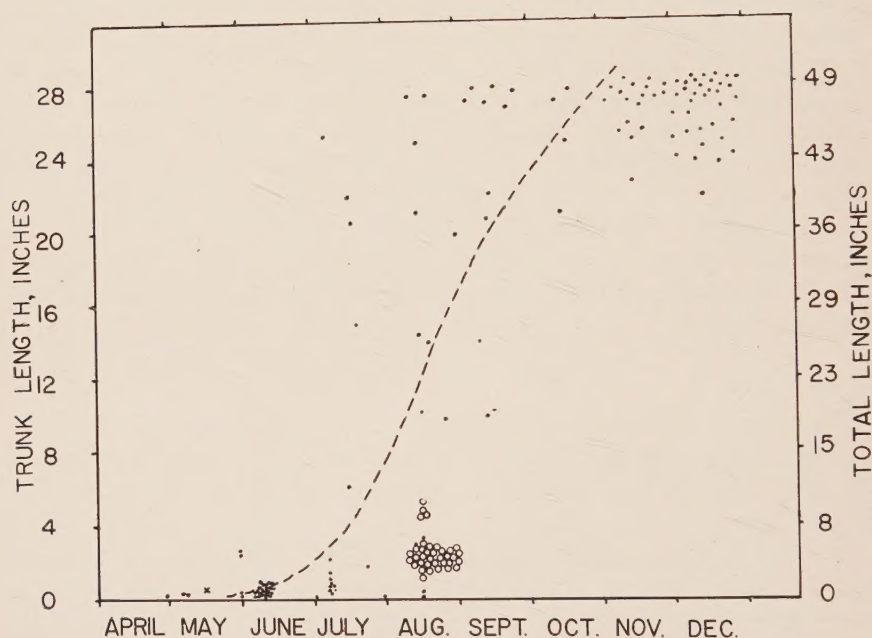


FIGURE 3. Growth of young male and female Atlantic sailfish. Dots indicate actual total lengths plotted; circles indicate approximate lengths.

While the total number of young sailfish available for study is small, it should be noted that there was a constant effort made at all times of the year to collect the young. Intensive plankton and dipnet collections taken throughout the year by The Marine Laboratory and the U.S. Fish and Wildlife Service have not yielded, to the best of my knowledge, small specimens from months other than those here reported. Furthermore, in examining the stomachs of an extremely efficient fish collector, the common dolphin, *Coryphaena hippurus*, throughout the year in the Miami area, the author has found small sailfish which coincide with the data depicted in Figure 3. It is felt, therefore, that this growth is real, and not an artifact of differential collecting.

GROWTH OF ADULTS

The adult material discussed herein has been collected mostly from a small area of southeastern Florida, from Fort Lauderdale to the upper Florida Keys, a distance of about 100 miles. The results for each year are treated separately (Figs. 4 and 5); these data represent material obtained from Mr. Pflueger, plus a few which were

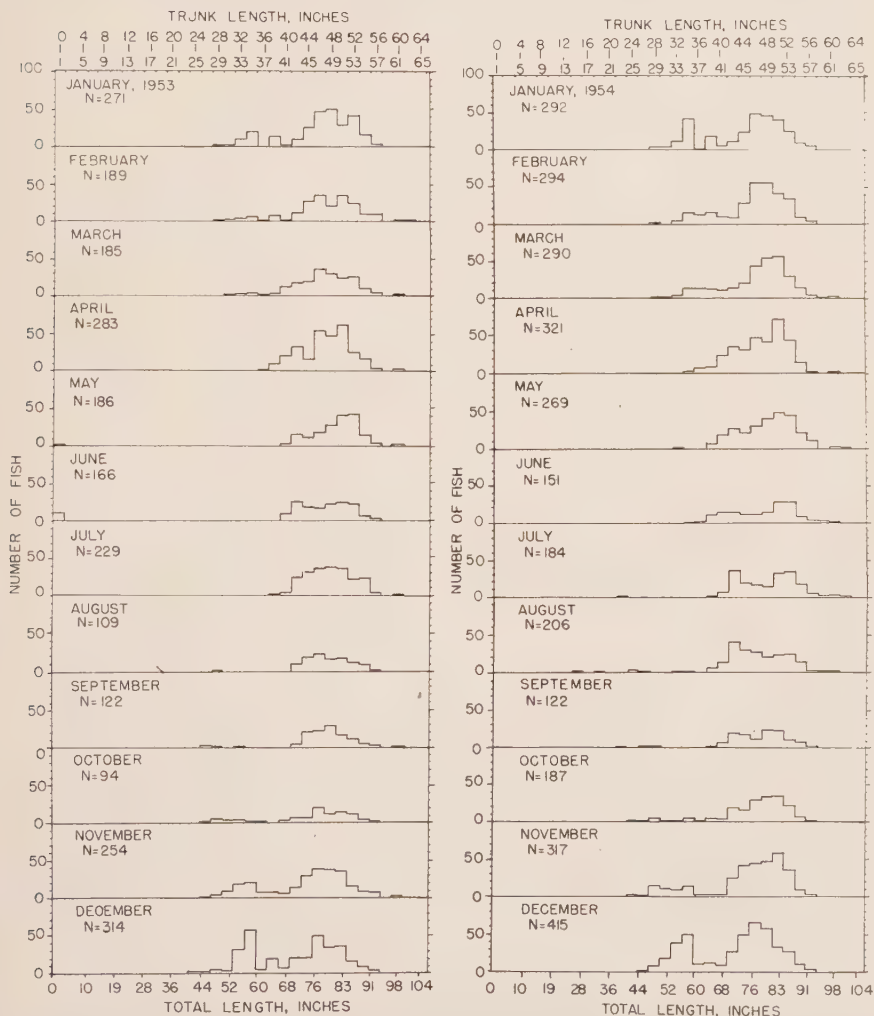


FIGURE 4. Left. Length-frequencies for Atlantic sailfish from southern Florida, 1953. Right. Length-frequencies for Atlantic sailfish from southern Florida, 1954.

TABLE 1
DATA FOR YOUNG SAILFISH TAKEN IN SOUTHERN FLORIDA, THE WESTERN BAHAMAS, AND THE GULF OF MEXICO (1936-1956).

Date collected	Location	Collector	Reference	Total length	Trunk length	No. of spec.
May 28, 1936	Biscayne Bay, Fla.	?	Fowler (1941)	2.5"	1.3"	1
Aug. 12, 1938	"Florida"		Beebe (1941)	2.9"	1.6"	1
July 6, 1940	Galveston, Texas	Duncan Holmes	Baughman (1941)	25.0"	14.0"	1
Aug. 31, 1941	Aranas Pass, Tex.	Lyle McCaleb	Baughman (1941)	20.0"	11.0"	1
July 7, 1948	Ft. Lauderdale, Fla.	J. T. Reese	Voss (1953)	<1"	<1"	2
July 7, 1948	Ft. Lauderdale, Fla.	J. T. Reese	Voss (1953)	1-2"	<1"	2
July 7, 1948	Miami Beach, Fla.	L. R. Rivas	Voss (1953)	<1"	<1"	4
July 7, 1948	Miami Beach, Fla.	L. R. Rivas	Voss (1953)	1-2"	<1"	1
March, 1951	Ft. Lauderdale, Fla.	J. T. Reese	Voss (1953)	<9"	—	1
April 29, 1951	Gulf of Mexico	E. L. Arnold	Arnold (1955)	<1"	<1"	1
Aug. 15, 1951	Gulf of Mexico	E. L. Arnold	Arnold (1955)	<1"	<1"	2
May 30, 1952	Gulf of Mexico	E. L. Arnold	Arnold (1955)	<3"	1-2"	1
June 12, 1952	Bimini, Bahamas	L. R. Rivas	Voss (1953)	<1"	<1"	1
May 29, 1953	Gun Cay, Bahamas	Univ. Miami	Voss (1953)	<1"	<1"	2
June 8, 1953	Gulf of Mexico	E. L. Arnold	Arnold (1955)	<1"	<1"	11
June 11, 1953	Gun Cay, Bahamas	Univ. Miami	Voss (1953)	<1"	<1"	1
July 2, 1953	Gun Cay, Bahamas	Univ. Miami	Voss (1953)	<1"	<1"	1
Aug.-Sept. 1953	N. Gulf of Mexico	Stewart Springer	Arnold (1955)	2-3"	<1"	30
July 19, 1954	Pompano Beach, Fla.	J. Borris (per J. T. Reese)	UMML (U. Miami Mar. Lab. Mus.)	15"	7.5"	1
May 5, 1955	Cabo Falso, Haiti	E. L. Arnold	Personal commun.	<1"	<1"	1
May 5, 1955	Bimini, Bahamas	F. J. Mather III	UMML	<1"	<1"	1
May 7, 1955	Gun Cay, Bahamas	L. R. Rivas	UMML	<1"	<1"	1
July 23, 1955	Cat Cay, Bahamas	E. L. Arnold	Personal commun.	1-2"	<1"	1
July 28, 1955	Bimini, Bahamas	L. R. Rivas	UMML	<1"	<1"	1
August, 1955	Gulf of Mexico	D. C. Tabb	UMML	3.3"	2.4"	1
August, 1955	Gulf of Mexico	E. L. Arnold	Personal commun.	1"	<1"	1
August, 1955	Gulf of Mexico	E. L. Arnold	Personal commun.	—	1-2"	3
August, 1955	Gulf of Mexico	E. L. Arnold	Personal commun.	—	3-4"	3
August, 1955	Gulf of Mexico	E. L. Arnold	Personal commun.	—	4-5"	1
Jan. 1956	Miami	E. L. Arnold	Personal commun.	31-34"	18-19"	1
June 5-11, 1956	Bimini, Bahamas	? D. P. deSylva	AI Pflueger UMML	<1"	<1"	13

TABLE 2
LENGTH-FREQUENCY (TRUNK LENGTH) DATA FOR 2402 ATLANTIC SAILFISH, 1953.

Trunk length interval, inches	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0-1					2	12	1					
20-21							1					
22-23							1		1			
24-25												
26-27												
28-29	2	1					1	1	3	1	1	2
30-31	2	2	2						1	5	4	2
32-33	10	3	2							4	8	5
34-35	20	6	3						1	4	18	4
36-37		1	1							1	20	31
38-39	14	7	2	2						1	7	57
40-41	1	2	12	10			1				7	5
42-43	10	11	17	20	3	10	5			3	5	19
44-45	26	27	19	32	16	26	25	10	5	7	13	7
46-47	47	34	35	53	19	19	32	19	21	7	29	19
48-49	50	20	29	46	28	23	37	23	22	20	38	48
50-51	29	34	23	60	42	25	38	16	30	11	37	34
52-53	41	23	25	24	43	23	37	17	17	14	35	35
54-55	16	8	9	16	15	7	22	12	12	11	15	16
56-57	3	8	4	3	4	3	24	10	5	4	8	8
58-59							3	1	3	1	7	3
60-61		1	2	2	2	1	2		1		2	
62-63		1										
Total number	271	189	185	283	186	166	229	109	122	94	254	314

de Sylva: Sailfish Growth

TABLE 3
LENGTH-FREQUENCY DATA (TRUNK LENGTH) FOR 3048 ATLANTIC SAILFISH, 1954.

Trunk length interval, inches	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
14-15								2				
16-17								1				
18-19												
20-21												
22-23							1	2	1	1	2	
24-25								1	1	1	1	
26-27												
28-29	4	1	1									1
30-31	4		1								1	8
32-33	11	4	3					1			14	18
34-35	41	15	13	1	1			1		1	10	38
36-37	1	12	13	6		2				5	13	49
38-39	18	16	12	8	6	11	1	6	1	5	2	12
40-41	5	10	11	23	18	14	7	13	6	4	2	9
42-43	11	8	13	35	27	14	35	40	19	19	25	27
44-45	24	28	21	31	21	12	18	29	18	16	42	48
46-47	48	56	43	46	30	12	16	27	12	29	44	65
48-49	46	56	54	41	40	14	14	20	23	34	47	57
50-51	40	41	56	71	48	28	32	23	22	35	59	33
52-53	25	34	29	43	44	28	34	24	10	22	35	27
54-55	9	9	13	14	21	8	17	13	7	7	9	10
56-57	5	4	4	1	10	4	5	2	1	1	2	3
58-59			1			2	1	1				
60-61			2	1	2	1	2	1				
62-63					1		1					
Total number	292	294	290	321	269	151	184	206	122	187	317	415

TABLE 4
LENGTH-FREQUENCY DATA (TRUNK LENGTH) FOR 3088 ATLANTIC SAILFISH, 1955.

Trunk length interval, inches	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
10-11									1			
12-13									1			
14-15												
16-17												
18-19	1											
20-21												
22-23										1	1	1
24-25											2	12
26-27											11	17
28-29								1	2	1	19	56
30-31	4	2									38	90
32-33	11	6	1								40	59
34-35	37	34	3	5							41	64
36-37	18	12	2	13							18	20
38-39	21	19	2	28							11	9
40-41	9	12	5	13	3		1	8		2	3	10
42-43	18	13	16	30	14	1	10	32	5	7	18	21
44-45	24	40	15	27	18	16	7	39	4	15	21	33
46-47	68	20	13	48	16	8	6	24	6	19	33	59
48-49	93	77	32	45	24	11	15	16	10	40	89	79
50-51	68	57	31	33	27	16	23	22	18	28	56	40
52-53	35	32	20	38	32	18	24	14	14	22	41	30
54-55	16	7	10	16	19	17	13	13	10	10	9	20
56-57	10	7	4	2	4	6	2	2	1	2	2	9
58-59						2						1
60-61		1		1							1	
Total number	434	339	154	291	166	119	102	172	73	154	454	630

TABLE 5
LENGTH-FREQUENCY DATA (TRUNK LENGTH) FOR 8630 ATLANTIC SAILFISH, 1953-1955 (ADULTS) AND 1936-1956 (YOUNG).

Trunk length interval, inches	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
0-1				1	7	26	6	35				
2-3							1	3				
4-5			1					4				
6-7							1					
8-9												
10-11								2	2			
12-13							1	2	1			
14-15												
16-17												
18-19	2						1	1	1			
20-21							1	1	1	1	1	1
22-23												14
24-25												20
26-27							1	1	6	2	13	69
28-29	6	2	1							10	37	56
30-31	10	4	3							6	66	112
32-33	32	13	6								74	170
34-35	98	55	19		1					5	27	35
36-37	19	25	16			1					20	40
38-39	53	42	16			13	3	7	1	5	10	26
40-41	15	24	28			29	12	21	6	9	56	67
42-43	39	32	46		9	56	70	82	29	33	92	100
44-45	74	111	55			48	57	87	43	38	115	172
46-47	163	110	91			37	59	74	40	68	173	170
48-49	189	153	115			48	67	52	63	85	150	108
50-51	137	132	110			69	92	62	57	77	91	73
52-53	101	89	74			32	80	50	36	55	26	38
54-55	41	24	32		55	32	54	36	22	21	11	15
56-57	18	19	12		18	13	10	5	5	4		1
58-59			1			4	1	1	1		3	
60-61		2	4		4	2	4	1				
62-63		1			1		1					
Total number	997	828	630	897	626	450	523	533	317	435	1025	1359

taken from other areas during those years. The lengths of these sailfish were grouped together in two-inch intervals, and were plotted by number for each month for 1953-1955.

In the data for 1953-1955 the location and apparent movements of the modes can be seen to be roughly equivalent for each year. Despite small samples for some months, notably September and October, polymodal groups appear throughout the year in most instances. Noticeable for each year is the presence of two main modal groups and the entrance of a new year class during the summer months.

GROWTH OF YOUNG AND ADULTS COMBINED

Due to the remarkable similarity for the frequency polygons for the corresponding months of each of the three years involved, it seems justified to combine these data, even though possible differences between year classes at the same age are masked by this procedure. This enables us to deal with a larger sample and emphasizes the differences between age groups. To this combined graph are added the data from Table 1 on young sailfish, bringing the total sample to 8630 fish. These data are presented in Table 5. The modes have been smoothed by a three-item moving average and criteria have been imposed as suggested by Iversen (1955):

"1. No modes have been sought in distributions containing less than 100 fish.

"2. Each mode must be separated from every other mode by troughs dipping at least 5 fish below modes after smoothing.

"3. Each mode must be present in the data for at least two not too widely separated months.

"4. At least two of the groups making up the mode must have no less than 15 individuals each before smoothing, or at least 10 individuals if the modal peak is present in two adjacent months.

"5. The mode must be the center group of a peak of the smoothed distribution or the center group of two or more minor peaks which differ by less than 5 fish in height."

Although Iversen's criteria were used essentially as presented, modes falling into his criteria are represented among any consecutive months by a solid line, whereas modal progression which does not qualify for these criteria but which is apparently real is indicated by a dashed line.

Young sailfish appear in the plankton from April until mid-August

(Fig. 5, right), according to our samples, and grow rapidly, as discussed previously. Taking June as an average starting point, by October they attain a modal value of 53 inches total length and a weight of about six pounds, and by January they are 61 inches long. Growth

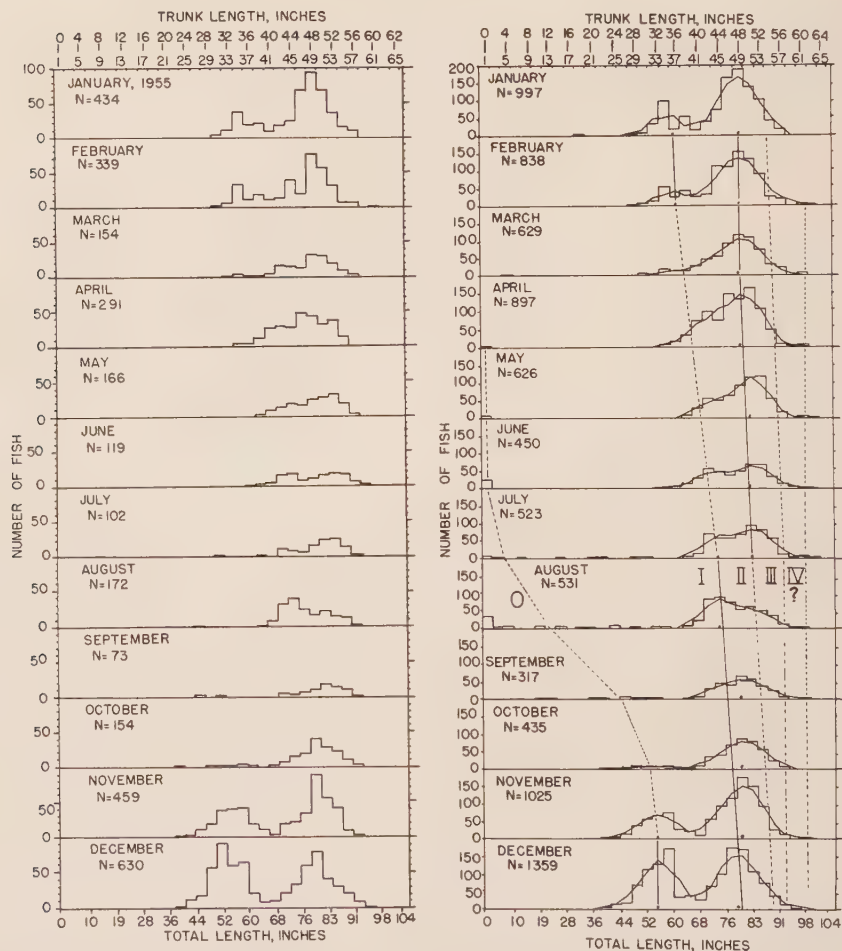


FIGURE 5. Left. Length-frequencies for Atlantic sailfish from southern Florida, 1955. Right. Length-frequencies of Atlantic sailfish. Fish less than 36 inches total length collected from 1936 to 1956; others are grouped data for 1953-1956. Solid line connecting successive modes represents growth using modal location criteria; dotted line represents probable growth. Roman numerals represent age class of fish.

is relatively slow from this point and by the following June, at the age of one year, they have grown to about 72 inches and a weight of about 21 pounds. By the time they have attained one and one-half years they are about 80 inches and weigh about 33 pounds. By their second summer they are approximately 85 inches long and weigh about 43 pounds. Subsequent growth is difficult to assess with accuracy, since, using the imposed criteria, modes are not discernible.

TABLE 6
GROWTH OF ATLANTIC SAILFISH FROM SOUTHERN FLORIDA.

Age in months	Modal total length, inches	Mean weight, pounds	Expected weight range
6	56	7	4-10
12	72	21	13-29
18	80	33	22-48
24	85	43	28-67
30	87	48	32-75
36	92	63	42-109
42	94	69	46-121

However, there would appear to be a gradual increase in growth to approximately 92 inches by their third summer, with an average weight of 63 pounds. The expected range of variation in weight is tremendous, and a two-year old fish averages 55 pounds with an expected range in weight, for a given modal length of 85 inches, of from 28 to 67 pounds; a three-year old fish averaging 63 pounds and having a modal length of 92 inches may be expected to weigh between 42 and 109 pounds (Figs. 6 and 7).

Speculation about age beyond this point seems desirable because of the presence of a modal group which occurs at about 98 inches during nearly every month of the year but which shows no progression in time. Extrapolation of growth lines beyond the three-year class shows that these 98-inch fish would appear to be at least four years old. However, they may represent the extremely fast-growing fish of the three-year class, or those spawned earlier in the year. In any event, it appears that most of the population consists of fish that are less than three years old, as suggested by Voss (1956), and that mortality, or perhaps emigration into some other area, must be quite high. The latter possibility does not seem tenable since the intensive sport fishery which is carried on for sailfish along the Florida coast would undoubtedly disclose the whereabouts of older fish if they are at all plentiful. It is possible that older specimens may swim at

greater depths which are generally not fished by sailfish anglers. However, it would seem that fishing carried on for other species at these depths would undoubtedly turn up an occasional deep-swimming sailfish if it frequented these areas.

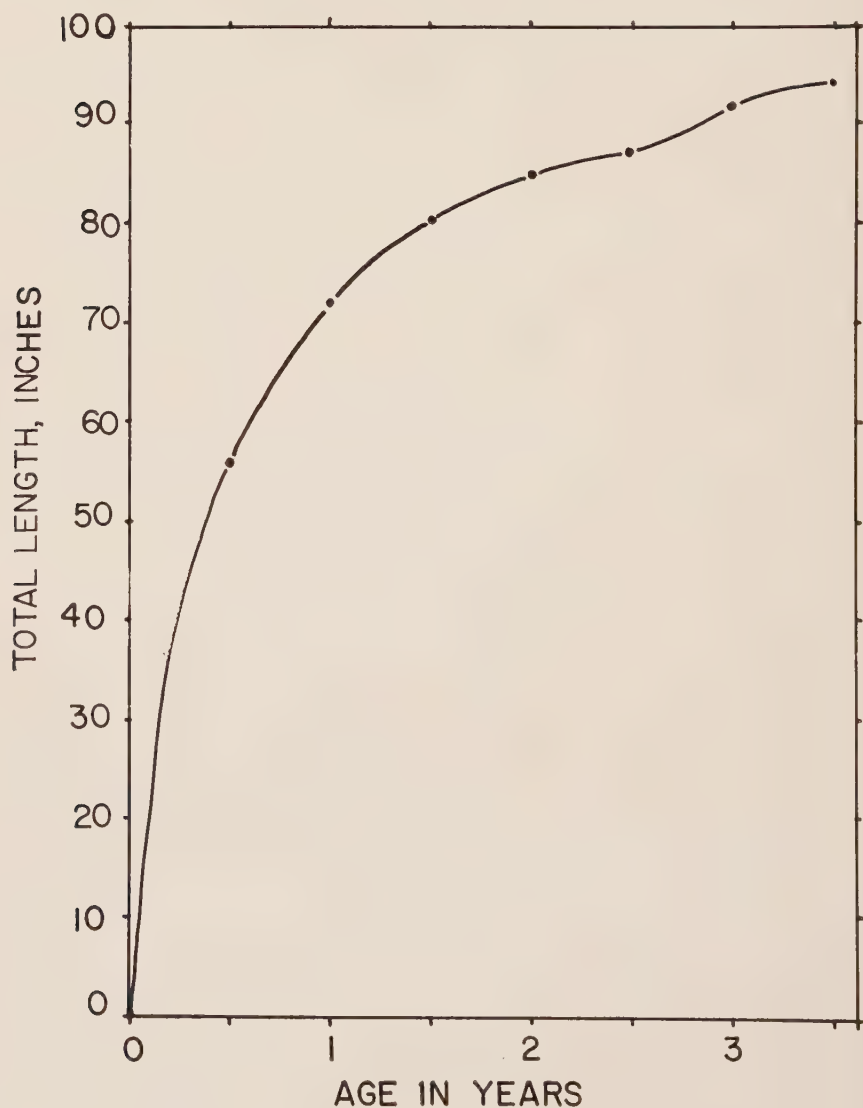


FIGURE 6. Age-length relationship for Atlantic sailfish.

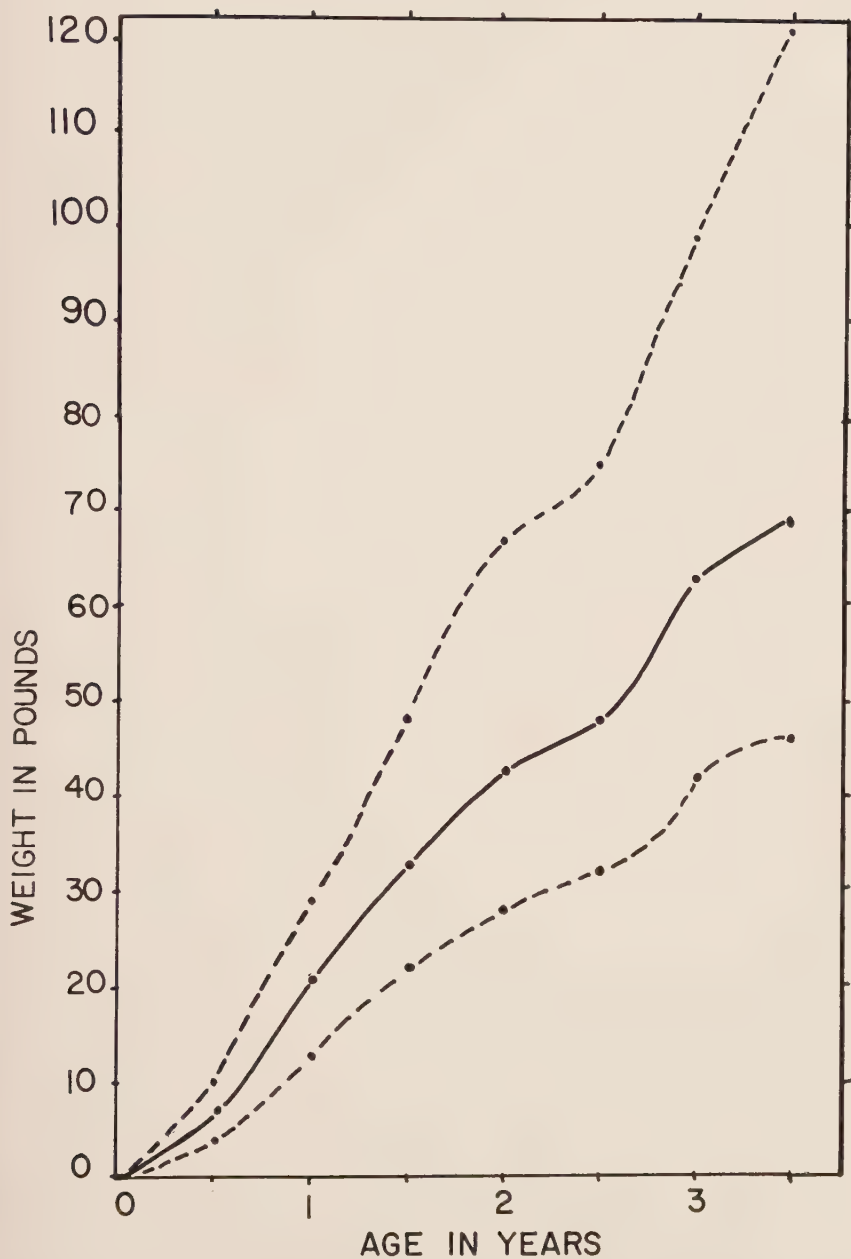


FIGURE 7. Age-weight relationship for Atlantic sailfish. Solid line represents average weight; broken lines represent expected range of variation.

It must be pointed out that the rapid increase in length over a short period of time is not as astonishing as it would seem when the length-weight relationship is considered (Fig. 2). Despite the fact that a sailfish attains a length of almost five feet in its first six months of life, this represents a weight of only about seven pounds, and is not extraordinary growth in the light of what is known about the growth rate of other oceanic fishes such as the bluefin, *Thunnus thynnus*, yellowfin, *Thunnus albacares*, and bigeye tunas which are closely related to the sailfish.

DISCUSSION AND CONCLUSIONS

The foregoing treatment of age and growth of sailfish is based on an abundance of adult and a dearth of young specimens. While it is felt that the figures arrived at in this discussion probably approximate average or modal figures, there are several possible sources of error. Most important, sex determinations were not available for correlation with the growth data. At first, a rapid growth differentiation between the sexes was considered, but inspection of the smoothly progressing modes, with no hint of splitting of the sexes as the adult stage is approached, seems to make this hypothesis unlikely. Although examination of the sex of these fish has not been generally practicable, inasmuch as they are saved intact for the taxidermist's shop, Mr. Pflueger informs me (personal communication) that he has found both male and female sailfish over eight and one-half feet long, thus precluding the assumption of complete differential mortality at an early age. However, it is possible that a large *proportion* of one sex dies off, and the possibility of differential growth and mortality of the sexes in this regard should be investigated.

There is a general scarcity of the young (Figure 5) during September and October but their numbers increase greatly during the next two months. The small sample available during September and October may be explained as follows: this is a period of storm activity and rough seas, and the young probably avoid the turbulent surface waters. Second, since it is a relatively poor swimmer at this stage, and because its mouth is still small, it is probably not able to keep up with or be hooked by the rather large, rapidly-trolled bait used by the angler. Thirdly, as noted by Voss (1956), these small sailfish probably are gradually moving back down the coast from the Carolinas where they drifted as young earlier in the year, and are just beginning to appear in the southern Florida area, where the majority

of fishing effort is expended, and thus few are available to the fishermen at this time.

Two matters of importance should be stressed. It seems evident that natural mortality is high. For any given month there are only two major year classes which support the sport fishery. During the winter the fishery is almost entirely dependent upon specimens which are respectively about six months, and about 18 months old; during the summer the fishery is exploiting largely one- and two-year old fish. It does not seem reasonable to suppose that the relatively ineffective sport fishery is harvesting the sailfish before they reach four years of age. Rather it appears that natural mortality is the reason for the lack of older fish.

Presently, there is a Florida law prohibiting the possession of more than two sailfish by one person in one day. Furthermore, this law prohibits the sale of this species. The concept of conservation in its broadest sense (Idyll, 1952) stresses the waste of a resource by *underexploitation* as well as by *overexploitation*. Clearly, if most sailfish die after two or three years of life such a law would appear to have little conservation value. The practice of releasing fish intact is a commendable practice from the point of view of sportsmanship, adds incentive to a day's fishing, and allows the same fish to be caught by several anglers. From a conservation standpoint, however, it has little or no justification, as the fish over 7 feet apparently have a very brief life span left. However, it would be advisable to tag and release as many small fish (under seven feet) as possible to obtain further information on age, growth and migratory pattern.

In this connection, during the tagging program conducted by The Marine Laboratory over the past eight years, the percentage of tag returns has been very low. It is likely that most sailfish tagged are two or three years old, so that the probability of their living to be recaptured, barring injury during tagging, is rather low. Therefore, it is suggested that the tagging program be intensified during the winter months and concentrated mainly on the small sailfish less than seven feet long.

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SEA-LEVEL FLUCTUATIONS AT CHARLESTON, SOUTH CAROLINA

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ABSTRACT

The relation of daily winds and sea-levels was studied on the southeastern coast of the United States during 10 months in 1951 and 4 months in other years. Several methods were used to eliminate the effect of wind and allow examination of the residual sea-level changes. Daily, weekly, semi-annual, and year-to-year variations were observed. The first three types of variations amounted roughly to 1 foot; year-to-year differences were as great as 0.4 feet. Wind action on the shoal water over the continental shelf brought about the daily fluctuations. The remainder of the variations were derived primarily from the deep water beyond the shelf.

INTRODUCTION

Fluctuations in monthly sea-level along the southeastern Atlantic coast of the United States have been related both to variations in strength of the Gulf Stream and to the effects of local winds on the shallow coastal waters (Montgomery, 1938). However, the determination of the relative magnitudes of the dynamic and wind effects was not attempted. Trend toward higher annual mean sea-levels during the last 30 years have been correlated with increasing frequency of onshore wind (De Veaux, 1955), although whether or not the wind strength was sufficient to cause all or only part of the observed rise was not quantitatively considered. It is the purpose of this paper to evaluate the wind effect for periods from one day to a month and, after its separation, to characterize the residual sea-level fluctuations.

CHARACTERISTICS OF THE AREA STUDIED

Wind and sea-level fluctuations were studied at Charleston, South Carolina, where tidal heights were recorded² in the seaward portion of an estuarine system fed by the Cooper, Ashley, and Wando Rivers. The estuarine system emptied into the sea through a narrow opening protected by jetties. Average monthly salinities (1942-1952) at the tide gauge station varied between 14 0/00 in April and 19 0/00 in October, although on record during the period are salinities as high as 33 0/00 and as low as 4 0/00 (U. S. Coast and Geodetic Survey,

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²At the Custom House wharf gauging station.

1953). The tide station is eight miles from the seaward end of the jetties, but branches of the estuary meander through marshland 10-20 miles landward of this station.

METHODS

The geostrophic wind direction and velocity over an ocean area of 150 miles diameter adjoining the coast off Charleston was obtained from the pressure distribution at 1:30 A.M. on daily weather maps, following the method of Miller (1954). The wind at the sea surface was considered to be 20° to the left of the geostrophic wind direction and to be $2/3$ of the geostrophic wind velocity. The direction of drift of water, of maximum slope of sea surface, and ultimately of greatest rise or fall of sea-level at the coast was considered to be 40° to the right of the surface wind direction, as found by Miller at Atlantic City. The velocity component of the wind producing a drift of water normal to the coast was obtained by multiplying the sine of the angle between drift of water and coastline by the wind velocity. Winds were split into those producing onshore and those producing offshore drifts.

Monthly resultant winds, made up from ships' observations over an approximately 50-year period, were taken from *Atlas of Climactic Charts of the Oceans* (U.S. Weather Bureau, 1938).

The average of hourly tidal heights, midnight to midnight, provided a tide gauge record representative of mean daily sea-level.¹ It was corrected for variation caused by departure of atmospheric pressure from normal, using the pressure at 1:30 A.M. Mean monthly sea-levels, using all values from 1921 to 1946, were taken from Pattullo et al. (1955).

Since the tide gauge record represented mean sea-level from midnight to midnight and since the wind force and direction were estimated at 1:30 A.M., a lag period of 10.5 hours resulted. Miller found a lag of 12 hours between wind fluctuations and maximum effect in raising and lowering sea-level.

A test of the methods used is shown here by Figure 1. A plot of the component of daily velocity normal to the coastline against the tide gauge record representing mean daily sea-level is shown for three conditions. There is one in which the direction of water drift is assumed to be the same as that of the wind, one in which drift is 20°

¹Averaging tidal heights over 24 hours instead of over a complete tidal cycle of 24 hours and 40 minutes produces a maximum error in estimating daily sea-level of 0.038 feet and mean monthly sea-level of 0.0013 feet.

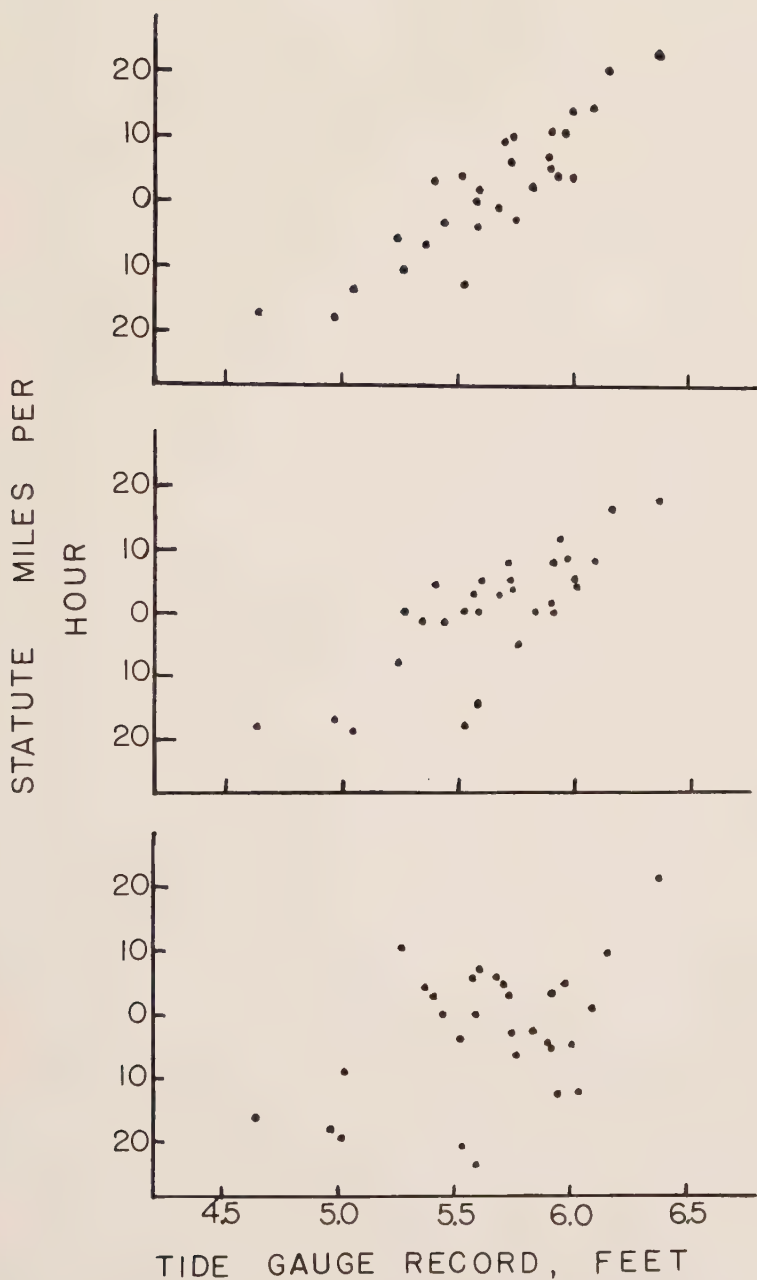


FIGURE 1. The relation of the wind velocity component normal to the coast and mean sea-level during November, 1951. Lower graph, water drift and wind direction are assumed the same; middle graph, water drift is assumed 20° to right of wind direction; upper graph, water drift is 40° to right of wind direction.

and one in which drift is 40° to the right of wind direction. The best correlation is obtained with a 40° deflection of drift and resulting maximum sea-level rise or fall. Further, the high degree of correlation, $r = 0.97$, would appear to indicate that the lag period used was correct. A plot where the square of the wind component is used showed no improvement in the linearity or the correlation of the relationship. According to theory, the resistance of the water (which produces drift and a proportional sea-level change) varies with the square of the wind velocity. However, a similar plot (Hellström, 1941, see page 142), where much higher wind velocities are used, shows clearly the curved relationship between water level and wind velocity.

RESULTS

Figure 2 shows for all the months of the year 1951 except January and March the relation between daily sea-level and the component of the onshore or offshore wind that produced a drift of water normal to the coast. The relation is roughly linear. In summer daily wind components were less than in fall, winter, and spring. Day-to-day sea-level fluctuations decreased in summer also, but not in proportion to the decrease of the components of wind velocity. This last feature stems from the greater horizontal as compared to vertical scatter of the points in summer when compared to other seasons. From June

TABLE 1
STATISTICAL CHARACTERISTICS OF WIND AND SEA-LEVEL

	b m.p.h./ft. *	r	$\frac{s_y}{s_x}$	s_y m.p.h.	s_x feet
November	26.9 $\pm$ 2.1	0.97	27.6	10.3	0.37
October	20.2 $\pm$ 8.2	0.68	29.8	10.3	0.35
April	20.0 $\pm$ 7.3	0.74	27.0	10.1	0.37
December	18.5 $\pm$ 3.7	0.89	20.0	9.5	0.47
February	17.3 $\pm$ 4.3	0.82	21.1	7.2	0.34
September	11.8 $\pm$ 6.2	0.60	19.7	4.9	0.25
August	9.2 $\pm$ 4.4	0.64	14.3	4.6	0.32
July	8.4 $\pm$ 4.2	0.48	17.6	4.8	0.28
June	7.1 $\pm$ 3.3	0.64	11.0	4.0	0.36
May	11.1 $\pm$ 6.3	0.46	24.1	7.8	0.32

*The limits of error of the regression coefficient are the extreme values it would have by chance in 1 out of 20 similar situations. Thus, the upper limit of August is 13.6, clearly less than any of the coefficients from October through April.

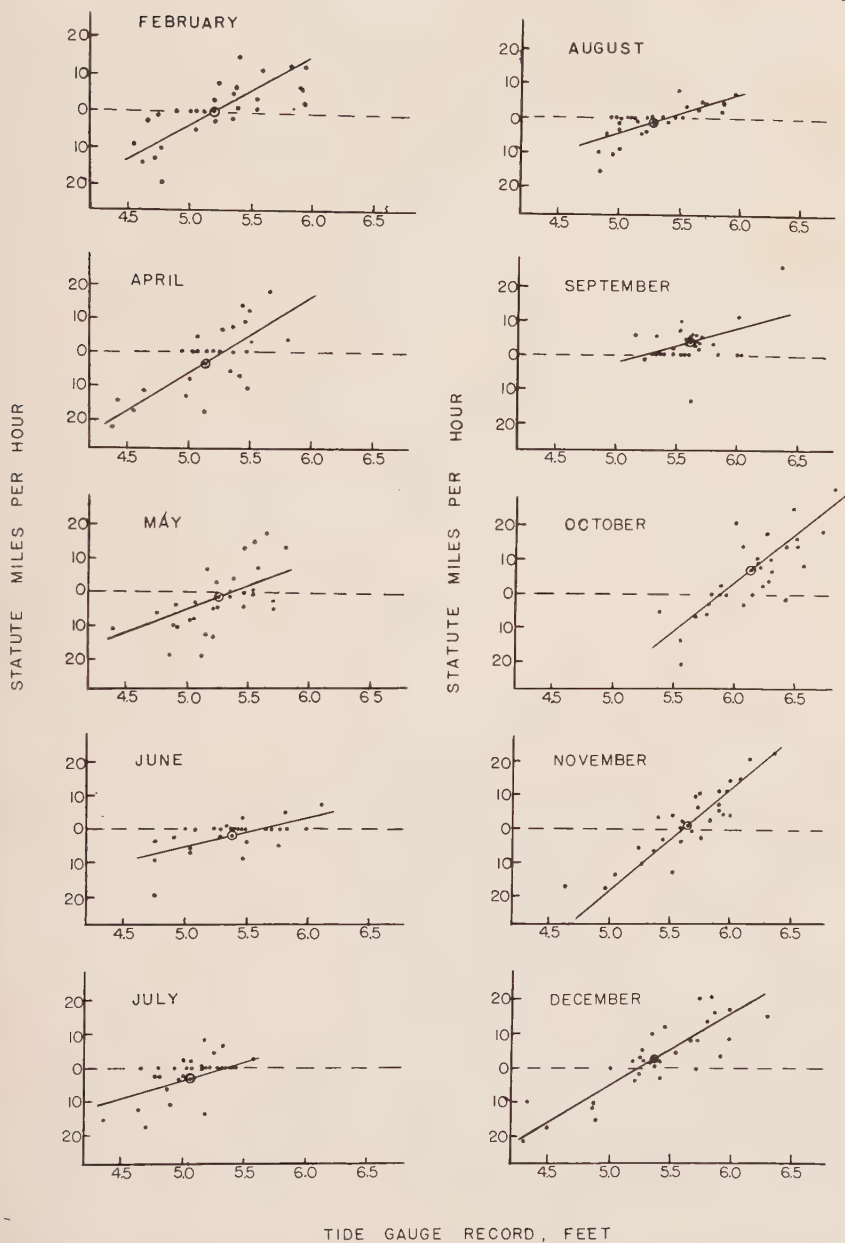


FIGURE 2. The relation of daily sea-level and wind velocity component producing a drift of water normal to the coast in 1951. Onshore wind component above dashed line; offshore component below dashed line.

through September the regression lines slope less steeply than from October through April. Table 1 shows that the regression coefficients of June through September differed significantly from the coefficients of the other months, with February on the borderline with respect to September and May clearly an exception.

The graphs in Figure 2 show a slightly greater proportion of winds causing onshore drifts in September and October and offshore drifts in April, June, and July. Daily values for sea-level were much higher in fall, particularly during October, than during the rest of the year. It is striking that during October all the daily sea-levels, except one, were higher than the daily sea-levels of July. The encircled points represent the mean wind component and the mean sea-level for the month. These points show a small net onshore wind drift in September, October, November, and December, and a slight net offshore drift during other months, except February. They show, however, considerably higher mean sea-levels in September, October, and November than at other times.

In Figure 3 are shown the day-to-day changes of sea-level as represented by the tide gauge records. A continuous line runs between sea-level heights associated with onshore and offshore wind components and through points having no wind components. Dashed lines delineate sea-level associated with components of 10 and 20 statute miles per hour. There were numberless fluctuations of several days' duration which represented most probably poor estimation of mean daily wind or possibly sudden changes in river flow. Poor estimation is also suggested by abrupt change in width between con-

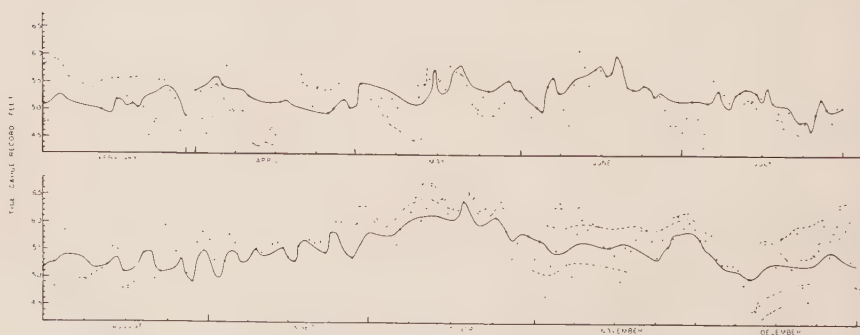


FIGURE 3. Day-to-day changes in sea-level. Solid line indicates sea-level having no onshore or offshore wind components producing drift normal to the coast. Dashed lines represent sea-levels associated with wind components of 10 and 20 statute miles per hour.

tours of 0, 10, and 20 miles per hour. Fluctuations during which the zero line ran through or close to a number of points consecutively occurred in the first week of June, the third week of July, and the first week of December. It would seem more likely that these fluctuations were real ones rather than large discrepancies due to the methods used. Sea-level with zero wind components rose from a winter minimum slightly during spring, fell to a second minimum in July, and rose to a maximum in October.

Daily wind and sea-level variations were studied for October of 4 other years between 1945 and 1954, as shown in Figure 4. October 1950 showed large variations of sea-level as the result of particularly hard winds causing onshore drifts. October 1949 and October 1954 are striking since sea-levels were considerably higher during the third weeks (encircled points) than during the other weeks, even though winds causing onshore drifts were negligible during the third weeks. These features are brought out even better by the graphs showing the daily progression of sea-level fluctuations. All of these months were characterized by net onshore wind components. Last, mean sea-level, although relatively high, varied very much.

STATISTICAL CHARACTERISTICS OF THE RELATION OF WIND AND SEA-LEVEL

In order to discover why the relation of wind and sea-level, represented by the regression lines in Figure 2, varied considerably throughout the year, the statistical quantities in Table 1 were computed. The relation between the regression coefficient, b , the correlation coefficient, r , and the standard deviations of wind components and sea-level, respectively s_y and s_x , is (Snedecor, 1948)

$$b = r \frac{s_y}{s_x}.$$

In November the correlation was highest and consequently the regression coefficient and the ratio of the standard deviations had almost the same value. October and April had smaller values of b , because the correlation coefficient was lower than in November. Regressions of December and February were somewhat lower still, because both

r and $\frac{s_y}{s_x}$ were smaller than in November. The extremely low values

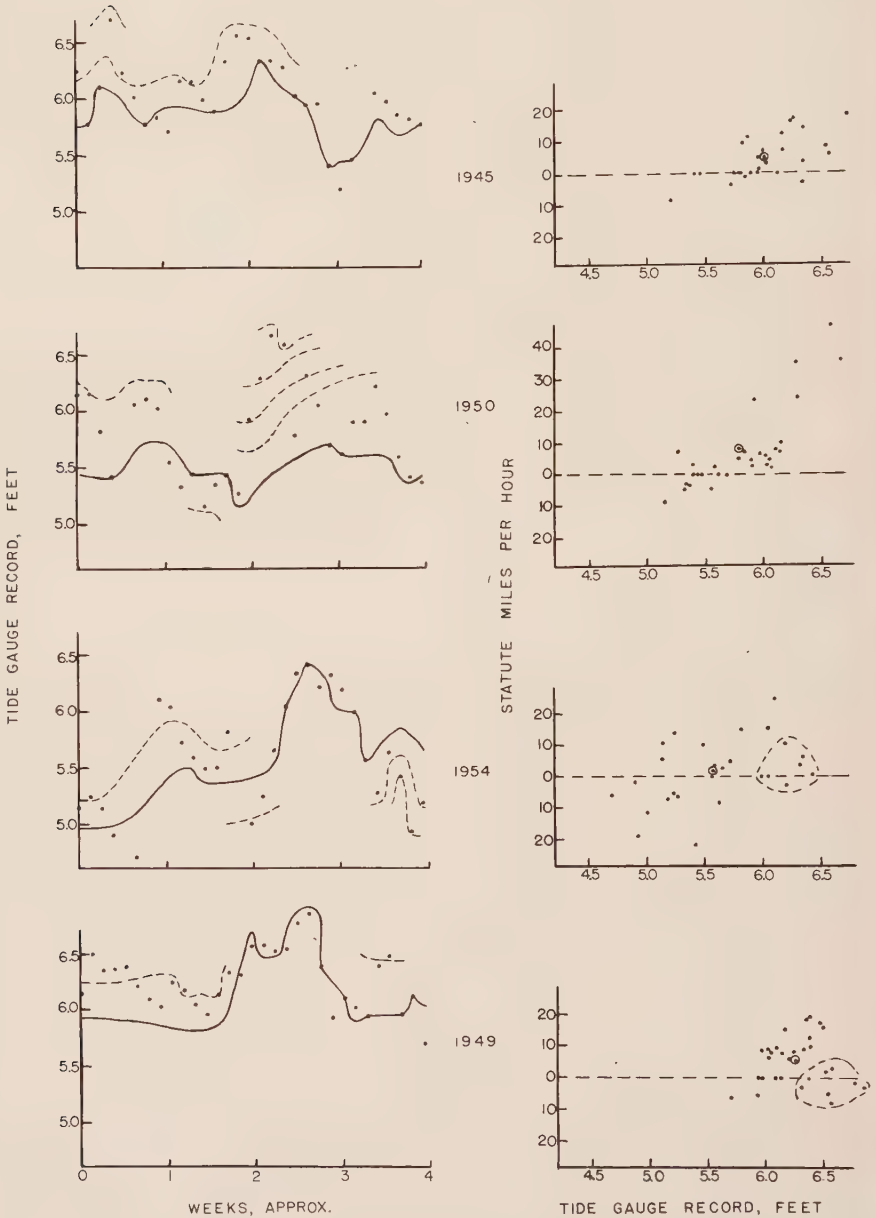


FIGURE 4. The relation of wind and sea-level in October of different years. To left: solid line indicates sea-level having no onshore or offshore wind components; dashed lines represent sea-levels associated with wind components of 10 and 20 statute miles per hour. To right: daily sea-level (horizontal scale) and wind component producing a drift of water normal to the coast (vertical scale).

of b from June through September had the lowest values of r and $\frac{s_y}{s_x}$. Lower values of s_y (i.e., light winds) from June through September than at other times produced the extremely low values of $\frac{s_y}{s_x}$ of summer and September. The regression coefficient for May was very low because of very poor correlation only.

Short period sea-level changes not caused by wind should mar the correlation of wind and sea level, particularly in summer when winds are light and sea-level is less controlled by wind. Low values of r in summer can be explained thus. When wind changes become smaller, sea-level changes should not diminish correspondingly if other causes change sea-levels. Low summer values of $\frac{s_y}{s_x}$ can be explained by this reasoning. Therefore, the changing relation of wind strength to sea-level variation can best be attributed to abrupt sea-level changes not due to wind.

THE COURSE OF MEAN MONTHLY SEA-LEVEL

The effect of net onshore or offshore wind drifts on sea-level for any month can be eliminated by drawing the regression of wind on sea-level for November through the encircled point representing mean sea-level and mean wind components for the month under consideration. Where the regression crosses the line for zero wind components, monthly mean sea-level with the effect of wind eliminated can be read off. In Figure 5 are shown monthly sea-levels with and without the elimination of wind effect. During 1951 the two estimates of sea-level ran very similar courses throughout the year, with two minima and two maxima, the maximum of fall being far the larger. Sea-level with wind effect eliminated had a somewhat lower fall maximum than that with wind effect included. The monthly sea-level fluctuations of 1951 were similar to the average between 1921 and 1946. Elimination of wind effect from the 1921-1946 levels changes the course of the monthly fluctuations in the same manner and to the same degree approximately as in 1951.

Monthly mean sea-levels for October of 1945, 1949, 1950, 1951, and 1954 are given in Table 2. Mean sea-level, wind effect included, was always somewhat higher than mean sea-level, wind effect eliminated. However, the great range of these monthly levels (see Figure 5)

TABLE 2
MEAN MONTHLY SEA-LEVEL IN OCTOBER

Year	Sea-Level, Feet	Sea-Level, Wind Effect Eliminated, Feet
1954	5.57	5.52
1950	5.81	5.55
1945	6.00	5.84
1951	6.12	5.90
1949	6.26	6.01

representing the maximum range in the 10-year period between 1945 and 1954, was lessened only 2/7 by elimination of wind effect. Thus, this range was brought about more by other factors than by different amounts of net onshore wind drift.

DISCUSSION

During the ten months studied in 1951 the minimum value of

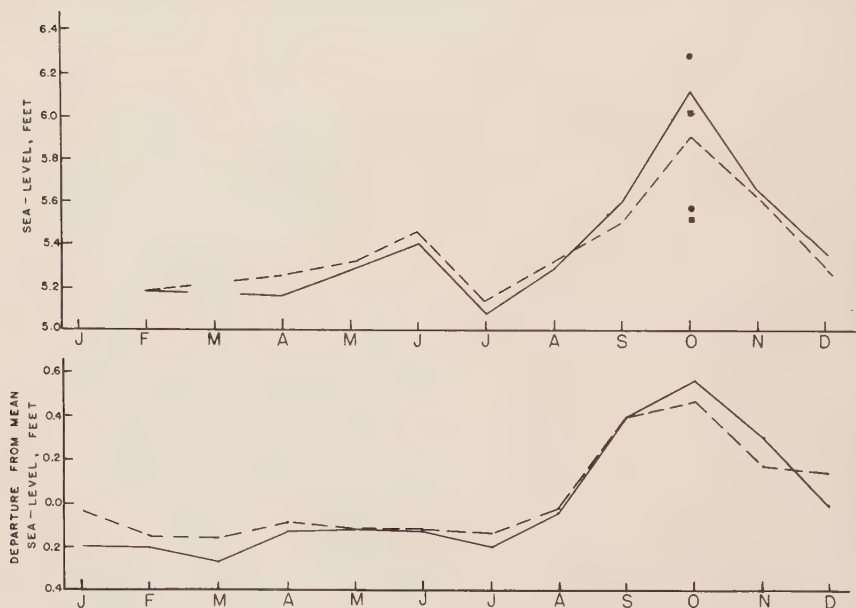


FIGURE 5. Mean monthly sea-level in 1951, upper graph, and over the period 1921-1946, lower graph. Solid line is sea-level with wind effect included; dashed line is sea-level with wind effect eliminated. Maximum and minimum sea-levels in October between 1945 and 1954 are shown by round points, wind effect included, and square points, wind effect eliminated.

daily sea-level, on July 5, was 0.86 feet below sea-level for zero wind effect averaged for the preceding and following three days. The maximum value, on October 14, was 0.65 feet above the weekly mean sea-level, wind effect eliminated. Thus, during 1951 the range of variation due to wind alone, 1.51 feet, was 59% of the extreme variation, 2.56 feet, due both to wind and to those factors that produce weekly and semi-annual variations of sea-level.

Wind, it is considered (Montgomery, 1938), produces variations by piling up or thinning out the shoal waters on the continental shelf. The relation between wind and sea-level is the regression of November. A 27-mile-per-hour wind producing a drift of water normal to the coast raises or lowers the water 1 foot in Charleston harbor. This value is exactly the same as that for Atlantic City (Miller, 1954), where a similar, shallow shelf is somewhat deeper but broader than off Charleston. Thus, the resistance of wind on water surface off Atlantic City would effect less change in elevation of a vertical column of water of unit area than off Charleston. But the greater breadth of shelf at Atlantic City should compensate for the greater depth, at least qualitatively, by providing a greater accumulation of elevation change at the shoreline.

Sea-level fluctuations of a week's duration amounted to about 1 foot in October, 1949, and October, 1951. It is improbable that the rises of sea-level were caused by increased river flows, since, as shown in Figure 6, general decreases in salinity did not occur during the third weeks. (Salinities were taken once a day at different stages of the tide.) Since water transport variations through the Florida Straits show good correlation with the weekly averages of the sea-level difference across the Straits (Wertheim, 1955), it is felt that the short-period changes not due to wind result similarly from transport changes in the near-by Gulf Stream complex. There is much uncertainty in this explanation, since it is necessary to assume that sea-level changes to the east of the stream are negligible, in order that the Charleston changes represent cross-stream slope changes.

During the 10 months studied in 1951 monthly mean sea-level minima were in February and July; maxima in June and October. The maximum range in this semi-annual variation, wind effect eliminated, was 0.83 feet or 77.5% of the range, 1.07 feet, with wind effect included. For the 26-year average the semi-annual variation without wind effect was 75% of the total variation. Wind over the continental shelf, therefore, plays a minor role in the semi-annual

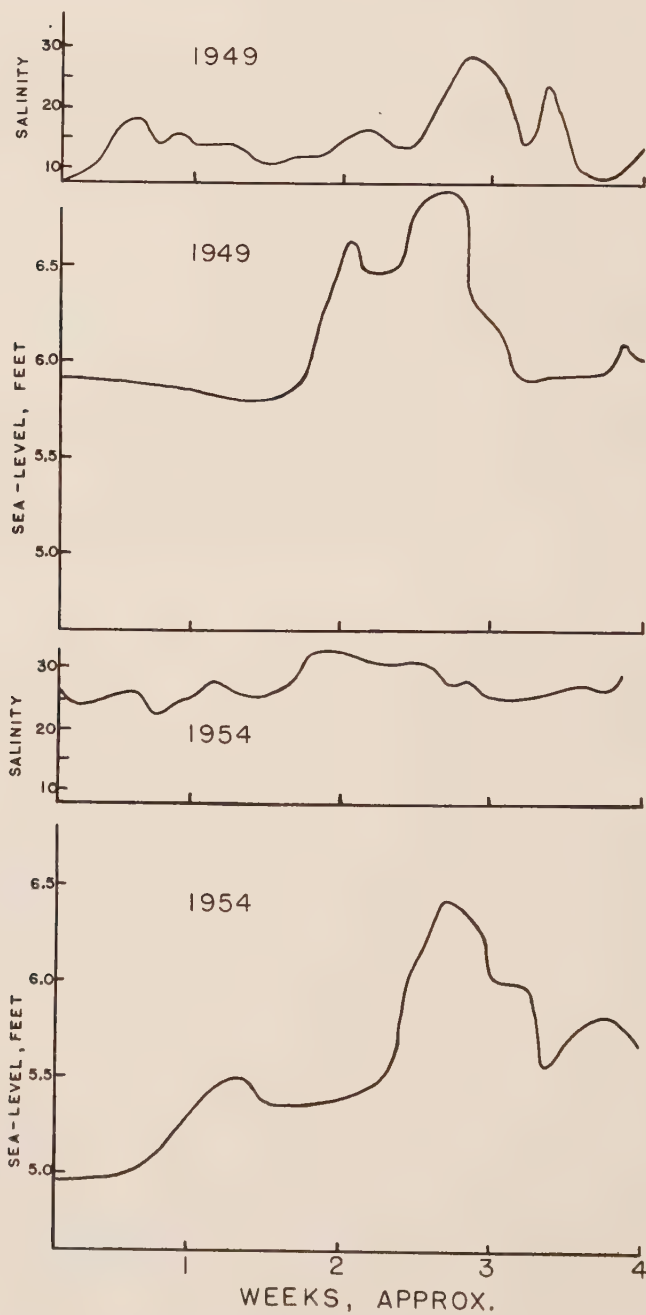


FIGURE 6. Daily salinity and sea-level with wind effect eliminated in October, 1949 and 1954.

variation. The remainder of the variation results primarily from a combination of sea-level changes in the water to the east of the Gulf Stream and changes in surface slope across the Stream due to changes in transport. Estimates of sea-level change well to the east of the Gulf Stream from the Bermuda tide gauge and from density computations (Pattullo et al., 1955) appear to vary considerably. The estimates of the Bermuda-Charleston difference vary considerably also (Montgomery, 1938, and Chase, 1954). Thus, although the present study makes possible an accurate estimate of sea-level oscillation on the western border of the Gulf Stream complex, uncertainties of estimation on the eastern side make it difficult to compare the surface slope changes with current variations. The disparity between slope (Bermuda-Charleston difference) and current shown by Chase would be relieved only slightly by elimination of wind effect at the Charleston gauge.

Zetler (1953) has studied the effect of increased river flow on sea-level at Charleston, showing that a salinity decrease from about 30‰ to 16.5‰ is accompanied by a rise of 0.09 feet. Mean monthly salinities of 25.0‰ and 16.6‰ occurred in October and July, 1951. Assuming a linear relation between sea-level and salinity, elimination of river effect would increase the semi-annual range by 0.05 feet, or 5% of the total variation. The range with effect of wind and river discharge eliminated would then be, tentatively, 0.89 feet.

Year-to-year variations in the annual maximum of sea-level between 1945 and 1954 had an extreme range of 0.69 feet, wind effect included, and 0.49, wind effect eliminated. The minor part played by wind is again demonstrated. The river effect, here, would narrow the range somewhat more, tentatively to 0.40 feet. The role of changes occurring beyond the shoal coastal water emerge as the primary source of the yearly differences in the maximum.

The author is deeply indebted to the U. S. Coast and Geodetic Survey for the use of tidal height data.

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ETIOLOGICAL STUDIES ON OYSTER MORTALITY. II. *POLYDORA WEBSTERI* HARTMANN—(POLYCHAETA: SPIONIDAE)¹

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ABSTRACT

Oysters from the major producing areas of Louisiana were found to be 100 per cent infected with the polychaete worm *Polydora websteri*. In Louisiana the population of *Polydora* was found to be highest in those areas remote from the sources of fresh water. In certain areas a positive correlation was found between the mortality of oysters and the degree of infestation by *P. websteri*, but this correlation was not substantiated by the results obtained from controlled laboratory experiments. It was concluded that the cause of mortality of oysters in Louisiana cannot be laid to *Polydora* per se, but that *P. websteri* as an abundant associated organism of the oyster community contributes a part toward the formation of a poor environment and in most cases is indicative of such an environment.

INTRODUCTION

Polydora websteri Hartmann, an annelid worm, is an associated organism of the oyster community. It lives in the crevices and holes in the valves of *Crassostrea virginica*; here it forms a U shaped tube which it enlarges as the worm increases in size. It frequently etches the margins of the shell, especially new shell growth, and also frequently penetrates the nacre of the valve, resulting in the formation of "blisters." A large population on or in a single oyster debilitates the host organism because the metabolic activities of the host are engaged in repair rather than in growth.

Hopkins (1947) has summarized the literature on *Polydora* infestations. From his account the following data was pertinent to this investigation: (1) *Polydora*, in all but two American publications, has been reported to injure oysters in a total of sixteen different ways and has been reported to be a dangerous oyster pest. (2) *Polydora* has been definitely incriminated in outbreaks of oyster mortality in Australia, Belgium, and in New Jersey. (3) The population of *Polydora* like many other animals has been subject to periodic fluctuations in abundance. (4) In Japanese oysters imported in 1940 to Grand Pass, Louisiana, heavy infestations of *Polydora* were accompanied by debilitation and high mortality.

¹Contribution No. 16 from the Contractual Research Program of the Louisiana Department of Wild Life and Fisheries, New Orleans, Louisiana.

During the course of the investigation on the causes of oyster mortality in southeastern Louisiana this organism naturally was suspected to be a causative organism of the reported unusual mortalities. Consequently, it was considered necessary to know the distribution and intensity of the infestation at selected localities in the area under investigation. Such knowledge when coupled with data from controlled experiments could then be used in the over-all etiological and ecological study on the causes of mortality.

Field surveys contribute important information to the knowledge of populations, but are unreliable in evaluating the possible pathological effects in a host-parasite association. Consequently, the field work on *P. websteri* was supplemented by experiments which were designed to throw some light on the seriousness of *P. websteri* as a direct causative agent of mortality of Louisiana oysters. These experiments were conducted at the Sister Lake Laboratory between May and October 1948, a period of time in which the greatest mortality of oysters occurred and in which *Polydora* approached its maximum concentration as an associated organism of the oyster community.

Grateful acknowledgment is made to Mr. L. L. Walters and Mr. James Pharis who assisted with the surveys. Dr. J. G. Mackin, Texas A. & M. Research Foundation, kindly furnished valuable advice on the procedures for the extraction of the worms, and with Dr. S. H. Hopkins furnished the oysters which were used in the laboratory experiments. Mr. G. Robert Lunz, Director Bears Bluff Laboratory, Wadmalow Island, South Carolina, served as biological consultant for the *Polydora* phase of the over-all investigation. Dr. Olga Hartmann checked the identity of the species of *Polydora*¹.

PROCEDURE

Eighteen stations, which were located in the major oyster producing areas, were established in southeastern Louisiana (Figure 1). The stations were sampled during April, August and December 1948 and constituted the first, second and third surveys respectively.

On each survey, a sample of 25 oysters was tonged from each station. Each of these was examined for *Polydora*. Ten oysters, of approximately the same size, were selected for the determination of

¹Personal copies of Dr. Hartmann's letters from Dr. S. H. Hopkins, Texas A. & M. Research Foundation, College Station, Texas. *P. hamata* Webster, 1879 has been reported from lower Barataria Bay.

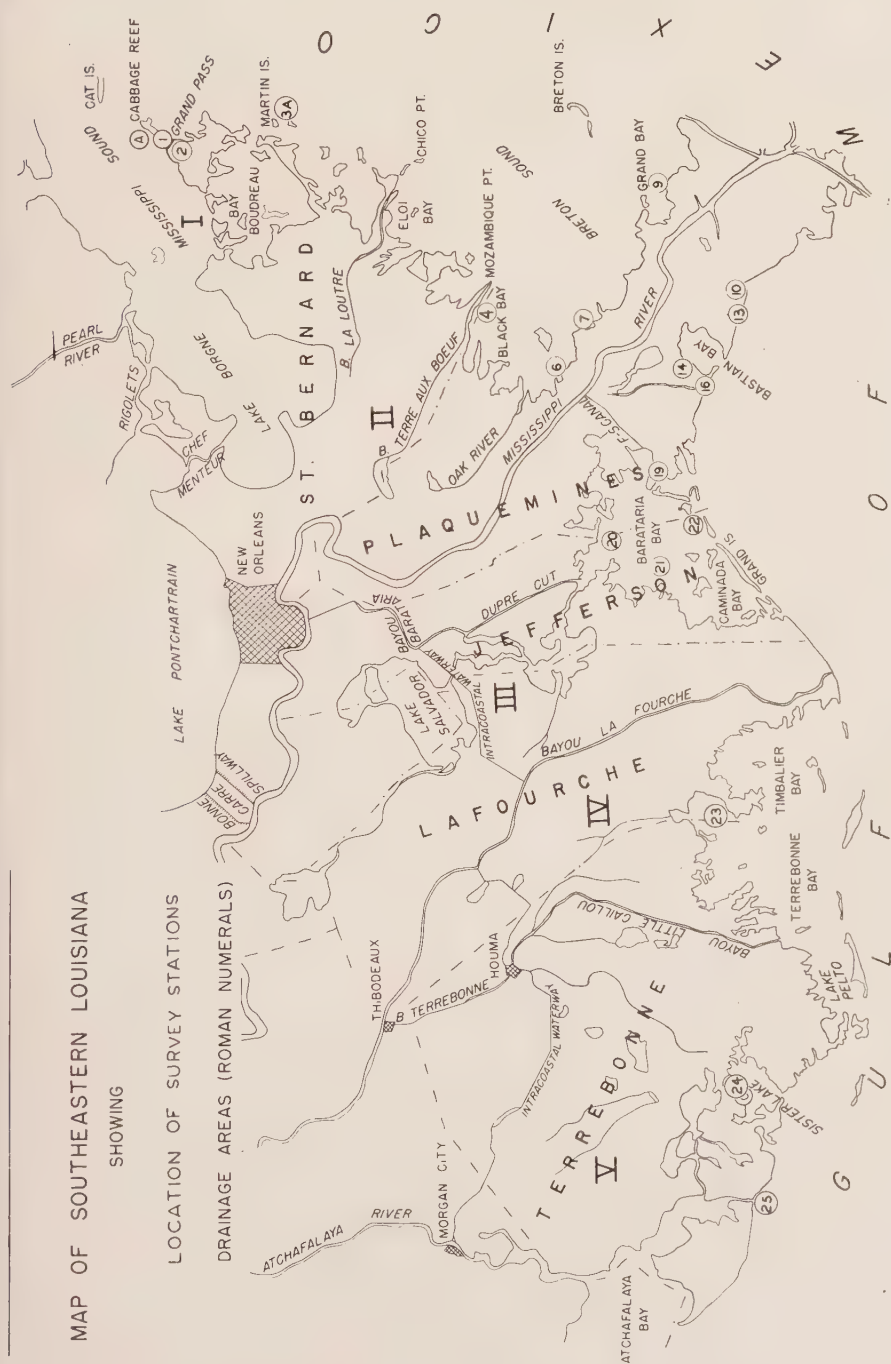


FIGURE 1. Map of southeastern Louisiana showing location of survey stations referred to in this study.

the *Polydora* population. These were measured for length, and from this, the average length of the sample was computed. Each oyster of the sample was individually washed with a stiff bristle brush, and was rinsed in fresh sea water until free from silt and mud. They were then placed in one-gallon wide mouth jars and covered with 0.005% solution of Carboic Acid (phenol) and salt water. They were kept in this solution for 12 hours. The oysters were removed after careful agitation in the phenol, but not until it was certain that no *Polydora* were exposed or were clinging to the shell. The phenol solution was carefully decanted. The worms and debris were transferred to smaller wide-mouth bottles for transportation to the laboratory. The oyster sample was then placed in fresh phenol solution for 4 hours. The same procedure was followed if the second treatment had produced worms. Five percent formalin was added to the decanted residue.

In the laboratory, the sample was again carefully decanted until free of solution. The volume of the remainder was measured in cubic centimeters. The number of worms in 1.0cc was counted and this figure was then multiplied by the total number of cubic centimeters of the sample. The shells of the oysters were examined under the dissecting microscope and an estimate, by count, was formulated as to the number of worms which remained in the shells after subjection to the phenol-extraction treatment. This was added to the count-volumetric conversion to give the total population of *Polydora* per 10 oysters. A degree of error was introduced by the presence of silt, but since each sample was subjected to the common error, no attempt was made to subtract this from the total.

Each of the three surveys was conducted by a different investigator, each, of course, following the same procedures for the extraction and the counting of the mudworms.

Hydrographic factors of salinity and temperature were taken at each station. In this report these have been supplemented by data which have been obtained from subsequent determinations. The mortality index for each station was established as a result of other surveys and experimentations and represents the average percent mortality based on individuals (Owen, 1951, 1953).

At the Sister Lake Laboratory an experiment was conducted which consisted of taking one hundred and sixty oysters known to have a high incidence of infestation of *Polydora* and dividing them into four groups of forty. Each group was placed in separate galvan-

ized wire trays (21" x 10.5" x 5") and attached to the dock in such a manner as to be submerged approximately one and one-half feet below the low tide level of the water. The oysters were measured and the average length for the respective groups was computed. They were then allowed to acclimatize for four days, during which time they were checked periodically.

In the laboratory glass aquaria were used as vats for the extraction of worms. Each tray was assigned to a separate vat to be used during the course of the experiment. Two trays of oysters were designated (Numbers 1 and 3) as experimental oysters and were treated with 0.005% phenol-salt water solution as previously outlined. The control trays (Numbers 2 and 4) were immersed in salt water and except for the phenol treatment they were handled in an identical manner as the experimental ones. To insure that a *Polydora* infestation would be controlled, Trays 1 and 3 were given the phenol treatment, every ten days between May 18 and October 21, 1948. At each period, the *Polydora* population of the experimental oysters was determined and both the experimental and control oysters were checked for mortality. At the termination of the experiment the remaining oysters were measured and the amount of shell growth determined by subtracting the initial lengths of the oysters from the final lengths.

This experiment with a single modification was partially repeated during November and December 1948. Eighty oysters from Sister Lake (Station 24) were used in two groups concurrent with eighty oysters from Lower Barataria Bay (Station 22). Thus, heavily infested oysters from an area of high mortality and high salinity were compared with moderately infested oysters from an area of low mortality and salinity. One tray of each group was treated four times during the two month period; the mortality of each group was checked at each treatment.

RESULTS

The shell examination of 1200 live oysters from 18 locations in Louisiana coastal waters showed a 100% infestation of *Polydora websteri*. The results of the three surveys are given in Table 1. Table 1 also shows the average length in mm of the oysters which were used for determining the *Polydora* population. A compilation of the data of Table 1 by the natural drainage areas showed that the *Polydora* population was highest during December in all areas

TABLE 1
INCIDENCE OF *Polydora websteri* INFESTATION IN *Crassostrea virginica* AT SELECTED
LOCATIONS IN APRIL, AUGUST AND DECEMBER 1948.

Survey Num- ber	Station Number																		No. of P. web- steri per 10 oysters	Average population per survey
	1	2	3A	4	6	7	9	10	13	14	16	19	20	21	22	23	24	25		
I	189	400	148	487	113	396	214	422	660	643	672	2585	1584	1558	2484	247	290	297	Oyster Bayou	743.6
II	88	75	—	30	667	330	138	155	289	1622	1716	3547	1654	1183	1690	477	1167	228	"	886.2
III	220	—	1110	180	140	900	1050	1070	2340	—	2820	1820	2380	3520	—	1970	2240	1040	"	1520.0
Avg. Popu- lation	166	237	629	236	310	542	467	549	1093	1132	1736	2651	1873	2420	2087	898	1231	522	Average	
	63.8	78.7	95.0	86.3	69.3	67.0	70.7	94.2	88.6	81.5	76.3	84.6	74.2	70.8	77.2	62.3	69.5	79.0	Avg. Length in mm	

except Area I. Table 2 gives the salinity and the mortality index for each station. The water temperature was approximately the same for all stations during the particular seasonal survey.

The results of the laboratory experiments are given in Table 3. After the initial deworming treatment (Table 3) the population of *Polydora* was negligible in the experimental oysters never going over an average of 20 per oyster.

DISCUSSION

Polydora websteri occurs in greater abundance in certain localities in the oyster growing areas of Louisiana than it does in others, and it has a seasonal cycle; the population as determined from this investigation reached its maximum numbers in December. This latter observation confirms the findings of Lunz (1941) for South Carolina oysters. The population was found to be significantly greater at Station 13 through 22 respectively, than at any of the other locations. Ecologically, this area, which for purposes of discussion has been designated as Area III, is different from the other four areas represented by the remaining stations (Figure 1). The main difference between Areas III & IV and the other areas lies in the lack of available, nutrient bearing fresh water. The exception to this within Area III are Stations 10 and 20. These two stations are located adjacent to fresh water outlets, and from the results of this investigation and from the results of other researches it is reflected in the comparatively lower salinities, correspondingly lower mortalities, and fewer detrimentally associated organisms. Likewise these environmental differences are reflected in the salinity index for the respective stations and thus for the five drainage areas in question. For example, Areas I, II and V are subjected to annual cyclic fluctuations in salinity that are positively correlated to the discharge of river water. Area III, and to a greater extent Area IV, experience a relatively constant high salinity at all periods of the year, except in the northern fringes of the area which are influenced by local marsh drainage. Thus, the lower extremities of Area III constituted a poor environment for the oyster community. In fact, there were no self sustaining oyster communities present in this region or in the abandoned (for oyster culture) lower region of Area IV.

From the field surveys there was a positive correlation between the mudworm population and mortality of oysters, except at Stations

TABLE 2
SALINITY INDEX AND MORTALITY INDEX FOR EACH STATION. DATA FROM 1947 THROUGH AUGUST 1950.

	1	2	3A	4	6	7	9	10	13	14	16	19	20	21	22	23	24	25
	Cabbage Reef	Bayou Pierre	Martin Island	Black Bay	American Bay	California Bay	Grand Bay	Sandy Point	Bayou Scofield	Bay Adam	Bastian Bay	Grand Ecaille	St. Mary's Point	Bassa-Bassa Bay	Lower Barataria	Lake Felicity	Sister Lake	Oyster Bayou
Mortality Index	5.5	30.9	40.0	5.8	6.9	11.5	43.5	21.8	42.0	34.7	80.0	55.8	23.3	36.0	58.1	22.6	8.4	9.6
Salinity Index	11.4	15.1	19.0	10.5	12.1	12.3	16.0	12.2	20.1	18.7	22.6	20.5	8.8	15.4	20.4	16.5	9.4	10.1

9, 20, and 24. The sizes of the oysters were not sufficiently different to influence the results significantly. From these correlations it could be concluded that *Polydora* is a causative agent of mortality. However, because of the results of the laboratory experiments and their relations to the negative correlation of Stations 20 and 24, this conclusion would be incorrect.

The laboratory experiments were conducted in an area of low mortality of oysters, an area of self-sustaining oyster communities, communities in which the oysters were the dominant organisms. Sister Lake (Station 24) is so located that the fresh water of the Atchafalaya River mixes with the salt-water of the Gulf of Mexico to create an optimum environment, especially because of the absence of predators and parasites, which were found to be more prevalent in areas of high salinities. The results of these experiments, which unfortunately were not conducted for the planned length of time because of storms and because the second experiment was not conducted during the hot summer months when it is known that "unusual" mortalities occur, showed that *P. websteri* per se was not a direct killer. Comparative mortalities between phenol-treated and untreated oysters and between the controls showed no signs of lethal effects in an optimum environment.

The *Polydora* free oysters added more shell than the *Polydora* infested oysters, which confirms the hypothesis that this organism generally by its perforating attack weakens the oyster and thus retards its growth as well as eroding new shell growth. Although the differential growth is not highly significant it must be remembered that it occurred in an optimum environmental area. It does not seem unreasonable to assume that in a region of rapid growth such as Bastian Bay that this finding would be repeated, in fact probably accentuated. Here it was not at all uncommon to find many blunt-billed oysters, the obvious cause of which was *Polydora*.

Thus *Polydora* and its relation to oyster diseases resolves itself to an understanding of the fluctuating ecological conditions. Somewhat like Station 24, Station 3A illustrates the point. The oyster communities of 3A fluctuate in direct proportion to the fresh water discharge of Pearl River and the opening of the Bonnet-Carre Spillway (Owen, 1950, Moore, 1946). The influx of fresh water in 1945 was sufficient to establish an oligohaline environment for a period of time necessary for the reestablishment of a natural oyster community (Butler, 1949). The contributions of fresh water

TABLE 3

RESULTS OF GROWTH AND MORTALITY BETWEEN PHENOL TREATED AND UNTREATED OYSTERS WITH HIGH INFESTATION OF *P. websteri*.

Exp. Tray Number and Type	Initial Average Size (length in mm)	Final Average Size	Polydora Recovered from initial treatment (avg. 40 oysters)	Total Mortality	Total Growth (length in mm)
I 1 Experimental	93.2	— ⁽¹⁾	434.5	6	—
I 3 Experimental	89.8	96.6	428.9	6	6.8
2 Control	88.3	— ⁽¹⁾	0	7	—
4 Control	88.2	92.6	0	9	4.4
5 Experimental A	83.0	— ⁽²⁾	151.0	3	—
II 7 Experimental B	89.3	—	39.5	1	—
6 Control A	80.0	—	0	3	—
8 Control B	81.3	—	0	4	—

(1) Trays 1 and 2 were lost as a result of a storm during the last two weeks of September.

(2) Trays dislodged during a storm in December and oysters recovered but not in proper arrangement.

are complex and in some cases not easily measurable. One effect of the oligohaline environment is to destroy or reduce the population of associated organisms which have a definite threshold tolerance for salinity. At Station 3A a prolific oyster population occurred in 1946 following the 1945 opening of the Spillway. The oyster population reached its peak in 1947, at which time the area was heavily exploited by man. High salinities gradually returned to the locality and as has been reported in the past (Moore, 1906) the normal cyclic re-establishment of the oyster community was prohibited. The dominance of the controlling organism, *Crassostrea virginica*, was insidiously weakened to the benefit of the detrimentally associated organisms, one of which was *Polydora websteri*.

Thus, in Louisiana it has been found that in areas of persistently high salinity the population of *Polydora websteri* was higher, apparently in direct ratio to the combined factors that contributed to an adverse environment for the oyster. This did not agree with the findings of Lunz (1941) in South Carolina. He found the infestation to be more prevalent in areas of low salinity.

The results of the investigation establishes a point that is applicable to the problem as a whole. *Polydora* is a part, like *Dermocystidium*, *Cliona*, *Thais*, *Martesia*, *Meneppi*, *Callinectes* and others, that is positively correlated to high mortality of oysters, but *Polydora* itself apparently is restricted in its direct effect by the factors of the environment.

Etiologically, *Polydora* in Louisiana can not be incriminated as a direct agent of mortality. As a debilitating pest it undoubtedly contributes a part toward the formation of adverse conditions of the oysters' environment.

CONCLUSIONS

1. Based on representative samples, oysters, from the major producing areas of Louisiana, were found to be 100% infected with the annelid worm, *Polydora websteri*.
2. In Louisiana the population of *P. websteri* was found to be greater in areas remote from sources of fresh water. These areas which are areas of rapid growth constitute the major "bedding" areas of the Louisiana oyster industry.
3. In certain areas a positive correlation was found between the mortality of oysters and the degree of infestation by *P. websteri*, but

this finding was not substantiated by controlled laboratory experiments.

4. The cause of mortality of oysters in Louisiana cannot be laid to *Polydora* per se, but rather it is concluded that *P. websteri* as an abundant associated organism of the oyster community contributes a part toward the formation of a poor environment and in most cases is indicative of such an environment.

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HYDROGRAPHY OF A POSITIVE, SHALLOW, TIDAL BAR-BUILT ESTUARY (REPORT ON THE HYDROGRAPHY OF THE POLLUTED AREA OF BISCAYNE BAY)^{1,2}

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ABSTRACT

In connection with a study of pollution in Biscayne Bay, at the south-eastern tip of the Florida peninsula, special attention has been given to the hydrography of the area. Generally, in studies of the ecology of tidal estuaries, the exchange of waters is of great significance in determining the character of the environment. Without a proper hydrographic investigation of the estuarine character of the area, it would be difficult to establish logical conclusions from the biological or bacteriological data.

Another reason for this hydrographic study was the fact that very few investigations of water circulation in shallow, bar-built estuaries, such as Biscayne Bay, have been performed. Due to the complexity of Biscayne Bay, all rigorous model estuaries would fail to apply to it. Therefore the hydrographic aspects present a specially difficult problem. Nevertheless, by means of carefully planned observations a reasonably clear understanding of the water exchange in Biscayne Bay has been reached.

Biscayne Bay is classed as a positive, shallow, tidal bar-built estuary, and the area studied is described in detail. Factors affecting the water circulation are discussed and special attention given also to the discharge of Miami River.

When the summer pollution situation of 1954 is compared with that of 1949 it is found that, due to the abnormally high summer river water discharge of 1954, pollution is less severe than would have been expected, except for the area close to and south of the mouth of the Miami River.

The general tidal conditions in Biscayne Bay are discussed as a basis for the tidal study of salinity and of the per cent saturation of dissolved oxygen. The horizontal salinity and dissolved oxygen distributions are discussed and their relationship studied. The horizontal distribution of per cent saturation of dissolved oxygen at different tidal phases is given. Corresponding studies of surface currents and surface salinities are explained.

The ratio between the tidal prism volume and the mean river water discharge is found to be around 24.

Finally the flushing number has been computed for the part of Biscayne Bay between Miami River and Government Cut and a most probable value of 0.3 has been derived.

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INTRODUCTION

The northernmost part of Biscayne Bay, north of Rickenbacker Causeway, between Miami and Miami Beach, with its causeways and many islands, both manmade and natural, is hydrographically an interesting estuary but one difficult to investigate thoroughly.

The fact that Biscayne Bay, after many years of pollution, has not received sewage effluents since Dec. 15, 1956, offered a unique opportunity to conduct ecological experiments on a broad scale, both before and after the outfalls were sealed. This work involved: (1) a detailed exhaustive preliminary study of the various factors; and, (2) a study of certain factors selected as a result of this earlier work, to be carried out over a period extending beyond the time when the sewage pollution had ceased. This survey, of which the hydrographic work is a part, was undertaken to correlate the extent of pollution with its ecological effects. In investigations of the ecology of tidal estuaries the exchanges of fresh and salt water are of primary importance in characterizing the environment. For example, the distribution of salinity and the extreme conditions to which sedentary organisms will be exposed are determined by these exchanges (Ketchum, 1951). Thus, without a proper hydrographic study of the estuarine character of the area it would be rather difficult or even impossible to deduce any orderly pattern in the other observations.

The survey of the hydrography of the polluted area of Biscayne Bay was begun November 11, 1953, and the field work was completed on September 19, 1954. The plans for the field work were made by Dr. Ilmo Hela, while the actual field observations were carried out by Mr. Clarence A. Carpenter, Jr., and Mr. J. Kneeland McNulty. Analysis of the data was performed by Dr. Hela.

Prior to the present investigations, the most recent study of Biscayne Bay pollution was that given in a mimeographed report by Minkin (1949), which is based, in part, on another by Milliken (1949.) Both reports have helped in several ways, including the selection of suitable methods for the different approaches.

BISCAYNE BAY AS AN ESTUARY

The area under consideration is a typical estuary. Following Pritchard's (1952) reasoning the two primary physical factors which serve to classify a region as estuarine are: (1) the mixing of water whose physical and chemical properties are peculiar to the estuarine region,

with water of open sea origin; and, (2) the relatively large effect of bottom and/or lateral boundaries in defining the circulation pattern. Several authors have given definitions of estuaries. For the purpose of this report only that of Pritchard (1952) applies: an estuary is a semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea water.

Further, the area under consideration in this report is a positive estuary since in it a mixture of low salinity estuarine water and sea water is found. In a positive estuary the fresh water which enters from the river is mixed with the sea water and through processes of advection and diffusion becomes distributed throughout the estuary. Miami River, and to a considerably lesser extent Arch Creek, Biscayne Canal, and Little River Canal, serve to justify considering Biscayne Bay as a positive estuary.

Geomorphologically Biscayne Bay or, more specifically, the northern part of it, belongs to the large group of estuaries which result from the development of an offshore bar on a shore line of low relief and shallow water. According to Pritchard (1952) the characteristic features of bar-built estuaries are: (1) a relatively small channel connecting the estuary with the ocean; and, (2) shallow depths within the estuary. Because of the narrowness of the channel, the tidal velocities are usually large in and near it, but are relatively small within the estuary. However, as a result of the shallow depths within the bar-built estuary, even these small tidal velocities contribute significantly to the mixing between the sea water and the land drainage.

Finally, Stommel (1951) has suggested a classification scheme for estuaries based upon the predominant physical causes of movement and mixing of water in the estuary. These causes of mixing may be either tidal, meteorological, or hydrological. In many estuaries no single cause of movement and mixing predominates. In several bar-built estuaries, provided that in the corresponding sea area the tidal range is not negligible, the tidal motion will dominate near the channel connecting the estuary with the ocean. Well within the "sound" or "bay", however, wind may also contribute appreciably to the motion and mixing. Since Biscayne Bay is divided by islands, both natural and artificial, and by causeways into several minor sub-areas, it really resembles a number of "channels." Thus the tidal effects, in spite of the relatively limited tidal range, predominate over motion and mixing brought about either meteorologically or hydrologically.

In summary, the northern part of Biscayne Bay, north of the Rick-

enbacker Causeway, is primarily a positive bar-built estuary where the movement and mixing of water are brought about mainly by tides, and to a lesser degree meteorologically and hydrologically.

As pointed out by Pritchard (1952), in some coastal plain estuaries and especially in bar-built estuaries, particularly in those with depths of less than 20 feet, vertical stratification appears to be lacking and the two-layer circulation pattern is not well developed. Ketchum (1950) has suggested that the salinity balance within an estuary of this type is maintained by horizontal mixing due to the oscillatory tidal motion. This is certainly the case in Biscayne Bay. The shallower areas of the Bay constitute a one-layer system, although the Main Ship Channel is sufficiently stratified to constitute a two-layer system, except during the later part of the flood tide, when the waters are sufficiently mixed vertically to be considered as a one-layer system. Depth observations in the Main Ship Channel in the first progress report of this investigation (Hela, 1955) are referred to.

DESCRIPTION OF THE AREA STUDIED

Greater Miami, situated in Dade County at the southeastern coast of Florida, is protected from the open ocean of the Straits of Florida, by a string of islands, of which Miami Beach, Fisher Island, Virginia Key and Key Biscayne are the most important. The northernmost part of the A-shaped Biscayne Bay, the total length of which is about 20 miles, is more completely cut off from the ocean water by the above islands and causeways. The same northern part of the Bay also suffers from the polluting effect of Greater Miami. Thus, for the purpose of this report, Biscayne Bay is used to designate only the portion north of the Rickenbacker Causeway.

Biscayne Bay is crossed by five causeways and bridges. They are from north to south: Broad Causeway, 79th Street Causeway, Venetian Causeway, MacArthur Causeway and Rickenbacker Causeway. They conveniently divide the Bay into five sub-areas.

Four comparatively small fresh water rivers and canals drain their waters into the Bay. These are, starting from the north: Arch Creek; Biscayne Canal, Little River Canal, and Miami River. All have their source in the Everglades area, and come down to the Bay laden with organic matter, the color of their waters being very dark. The discharge of Miami River is greater than those of the other three combined. Miami River which runs through the towns of Hialeah, Miami

Springs, and Miami, has been until July 1, 1956, essentially an open sewer.

The northern apex of Biscayne Bay is open to the ocean at Baker's Haulover (Figure 1, St. 103). The Bay is also open to the ocean at Government Cut (St. 611), of the main navigation channel (Stations 611 through 602), which is approximately one-quarter of a mile wide and in which the depth of the artificial channel is about 30 feet at low tide. The southernmost part of the Bay area in question, between MacArthur and Rickenbacker Causeways, is open to the ocean at Norris Cut (St. 713). The same area is connected through the bridged cuts of Rickenbacker Causeway (St. 801 and 804) with the southernmost, almost non-polluted large part of the Bay, which is open to the ocean at Bear Cut (St. 1008) and south of Key Biscayne.

A narrow channel, part of the Intracoastal Waterway, connects the northern apex of the Bay with the southerly areas, roughly, through stations 41, 102, 43, 44, 203, 49, 51, 52, 402, 501, 55, 20, 62, and 804. The depth of the Intracoastal Waterway channel is eight feet at low tide. The whole Bay, apart from the 30 feet deep Main Ship Channel and from the eight feet deep Intracoastal Waterway channel, is quite shallow and averages less than six feet over the north and central areas, with many large areas less than three feet. The south portion is deeper at the middle of the Bay and averages from eight to ten feet in most places. The mean depths, at low tide, for the different areas, separated by the causeways, are, from north to south, 4, 6, 6, 8, and 9 feet.

The area of the Bay under consideration is about 7.04×10^8 ft.² or 25.3 square miles. The mean depth at low tide for the same area is 6.9 feet, and thus the volume of the Bay at low tide is 48.3×10^8 ft.³. The mean tidal range over the Bay is roughly 1.9 feet, but high tide and, similarly, low tide does not occur simultaneously over the whole area. Therefore, as the most probable tidal "range," indicating the changes in water volume, 1.85 instead of 1.9 feet was selected, and the volume of Biscayne Bay during a mean high tide was estimated to be 61.4×10^8 ft.³. Thus during each flood tide about 13.0×10^8 ft.³ of water, the tidal prism volume, is brought into the Bay, increasing water volume of the Bay by some 27 per cent.

HYDROGRAPHIC STATIONS

The 136 main stations of this study and station numbers used in the 1949 report of the Florida State Board of Health were listed in the

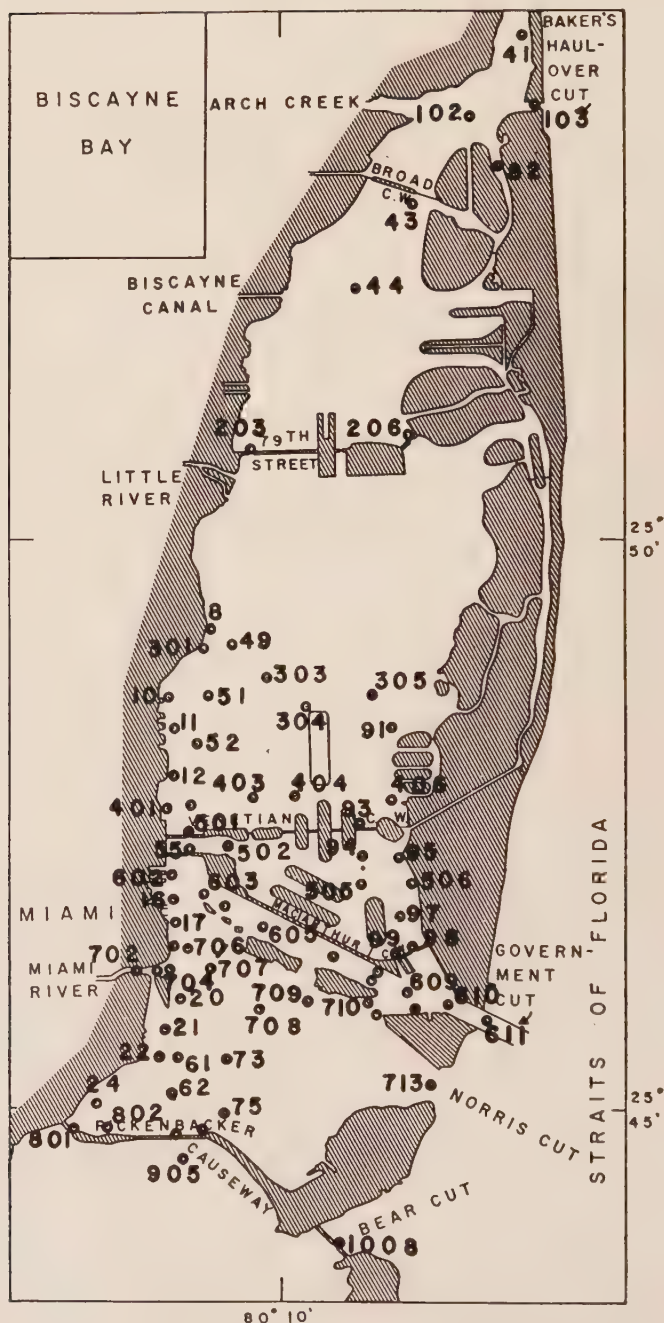


FIGURE 1. Northern part of Biscayne Bay with the hydrographic stations occupied for twelve hours.

first progress report (Hela, 1955). At these stations samples were taken for salinity and dissolved oxygen determinations, and the temperatures were recorded. All hydrographic samples, except those in a special depth experiment in the Main Ship Channel were actually sur-

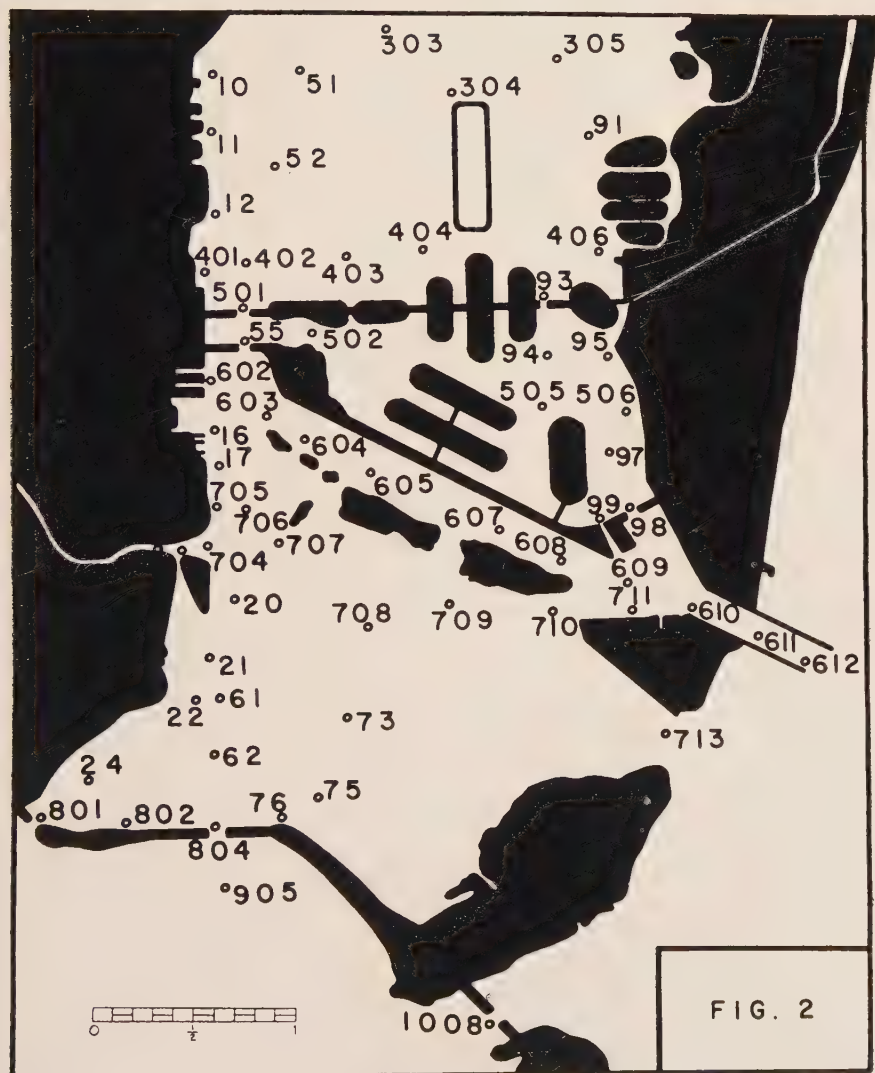


FIGURE 2. Pollution area of Biscayne Bay with the hydrographic stations occupied for twelve hours. (Scale represents one nautical mile).

face samples taken at a depth of about 18" below the surface. For current and salinity studies in the cuts and other critical points 19 additional stations were used.

During the first weeks of study, the tidal predominance in Biscayne Bay soon became evident. Actually, in most parts of the Bay tidal changes apparently are so significant that single observations have practically no value. Therefore 57 stations (Figure 1 or Figure 2) were each occupied at least once for a period of twelve hours for the study of tidal effects on salinity and dissolved oxygen, and 61 corresponding stations for the study of salinity and currents. This report is based mainly upon those tidal stations.

Determinations for dissolved oxygen were made by the sodium azide modification of the Winkler method. At first, chloride determinations were made by titrations with silver nitrate; later, hydrometers were used, since by this simpler method a sufficient degree of accuracy was obtained. The per cent saturation of dissolved oxygen was calculated from samples collected for dissolved oxygen content, chloride content and temperature.

FACTORS AFFECTING THE WATER CIRCULATION

The complex topography of Biscayne Bay makes the circulation pattern quite complicated. The actual influences at work to be taken into account are hydrological, meteorological, and tidal, all of which are either periodical or nonperiodical functions of time. For every set of active influences there must be also a system of reactive motions, based upon the submarine topography and upon the configuration of the coastline. The interplay of the active and reactive forces generally produces very complex circulation systems which may vary significantly from place to place and time to time within the same system (von Arx, 1952). Therefore, estuarine circulations are generally studied statistically when only the gross features can be obtained. In the case of estuaries with simple topography, studies in great detail are possible, though the amount of labor even in those cases may be considerable. Biscayne Bay offers an example for cases when a "synoptic" study in detail is almost impossible due to the complex pattern of channels and islands. Nevertheless, since the tidal influences predominate over the meteorological and hydrological, even in this case of relatively clear-cut pattern of the movements and mixing in the area may be obtained.

Before going into the study of the tidal influences, a few remarks

TABLE I
DISCHARGE OF MIAMI RIVER AT HIALEAH
IN FT. ³/SEC.

	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	Mean
October	—	1505	920	1031	428	450	799	1167	3596	2339	1356	535	801	981	1519	1245
November	—	1517	838	587	616	659	1439	1118	2934	2135	1305	794	821	1376	1473	1258
December	—	1114	705	394	736	473	1332	851	2332	1819	1139	802	780	1149	1300	1066
January	812	1142	575	311	515	314	1069	566	1966	1473	984	510	519	1034	1042	855
February	685	1131	469	222	259	882	467	420	1569	924	507	297	557	998	797	679
March	431	920	381	29	103	37	153	350	969	267	171	54	272	669	727	369
April	316	918	571	168	24	14	64	244	484	159	241	67	147	511	731	311
May	58	715	450	277	240	2	277	77	410	158	31	40	62	238	747	252
June	420	430	881	224	161	1	341	945	489	560	144	2	72	329	1121	410
July	284	776	1044	229	182	82	513	1333	382	715	377	286	345	424	1035	534
August	394	754	1190	283	378	67	546	1781	496	690	283	542	578	587	795	624
Sept'mb'r	885	700	1450	272	299	398	977	2293	1088	795	241	529	469	893	928	814
Mean		968	790	336	328	282	665	929	1393	1003	565	372	452	766	1018	701

must be given about the hydrological and meteorological influences.

DISCHARGE OF MIAMI RIVER

According to Surface Water Supply of the United States, published by the U.S. Department of the Interior (Table I), the water flow of Miami River, on a monthly basis, varies between 1 ft.³/sec. (June,

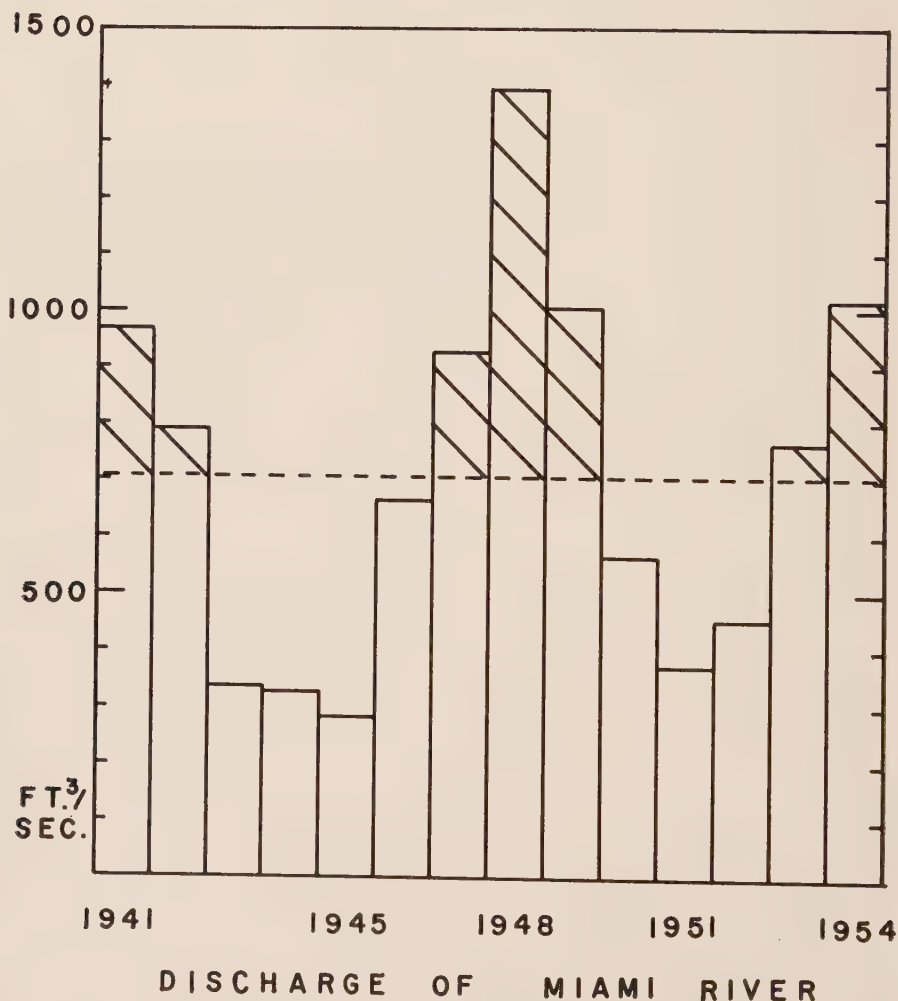


FIGURE 3. Yearly mean discharge values of Miami River at Hialeah, in cubic feet per second.

1945) and 3596 ft.³/sec. (October, 1948). Since these values are measured at Hialeah, Florida, and since it is estimated (Minkin, 1949) that flow at the mouth of Miami River is approximately 20 per cent larger, a maximum monthly discharge must be about 4300 ft.³/sec. This corresponds to an amount of 1.86×10^8 ft.³ during one whole tidal cycle. The mean discharge from the Miami River at Hialeah is only 701 ft.³/sec., and thus about 840 ft.³/sec. at the mouth, corresponding to 0.36×10^8 ft.³ during a tidal cycle. If it is assumed that the combined mean discharge of Arch Creek, Biscayne Canal, and Little River Canal is, roughly, 0.18×10^8 ft.³ during a tidal cycle, the total discharge into the northern Biscayne Bay is 0.54×10^8 ft.³ during a tidal cycle.

In Figure 3 the mean discharge values of Hialeah are given for different years. The large year-to-year fluctuations make it evident that, in order to obtain a normal or average pattern for the circulation

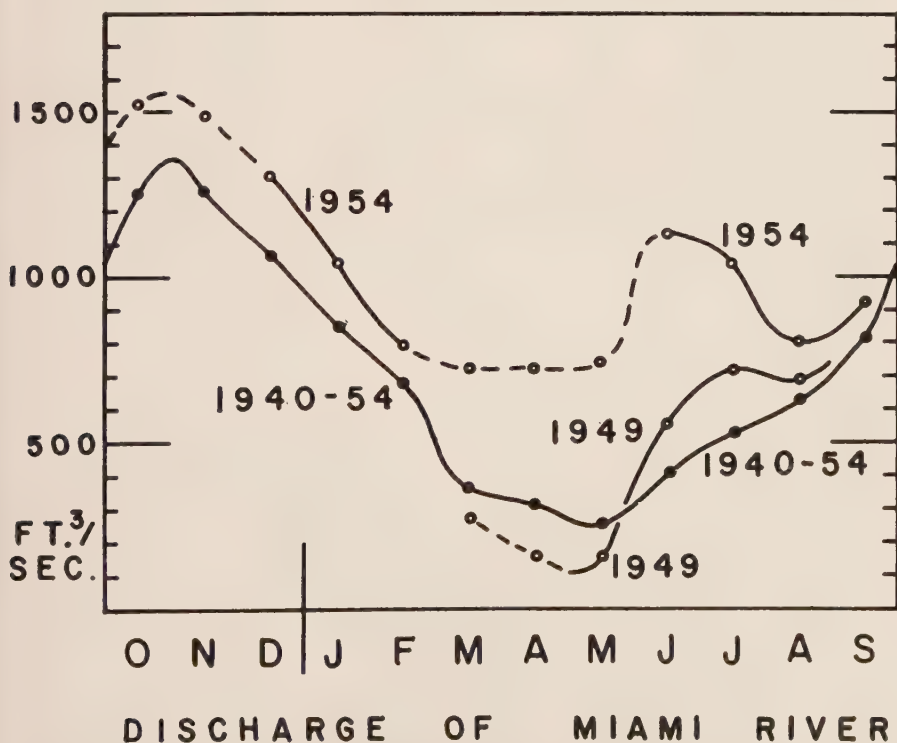


FIGURE 4. Annual cycle of discharge of Miami River at Hialeah, in cubic feet per second; corresponding data for 1949 and 1954.

in Biscayne Bay, the discharge values of the period of field-work must be compared with average discharge values.

Besides the year-to-year fluctuations the annual cycle must be considered. In Figure 4 the annual cycle is given on the basis of the years 1940-1954. The corresponding data for the periods of field-work of



FIGURE 5. Changes in per cent saturation of oxygen between the studies of 1949 and 1954.

1949 and 1954 are also indicated. The following data show that in 1949 the May-August discharge values were only 17 per cent above the normal, while in 1954 the June-August discharge was 88 per cent above the normal values.

Mean discharge, 1940-1954	701 ft. ³ /sec.
Mean discharge, 1940-1954, May-August	455 ft. ³ /sec.
Mean discharge, 1949, May-August	531 ft. ³ /sec.
Mean discharge, 1940-1954, June-August	523 ft. ³ /sec.
Mean discharge, 1954, June-August	984 ft. ³ /sec.

POLLUTION SITUATION OF 1954 AS COMPARED WITH 1949

In spite of the rapid increase in the population of Greater Miami, the high discharge values of Miami River and other fresh water outlets in summer 1954 have counteracted the increasing pollution of the Bay. In Figure 5 the changes in per cent saturation of dissolved oxygen between the studies of 1949 and of 1954 are indicated. In general, as shown by the plus signs, the per cent of saturation of dissolved oxygen was higher in 1954 than in 1949, and thus the pollution less pronounced as a result of the higher fresh water dilution. Nevertheless, at the mouth and south of the mouth of Miami River the per cent of saturation of oxygen was significantly less in 1954 than in 1949. This indicates that, without the establishment of the new sewage treatment system, the pollution of Biscayne Bay would have reached an unforeseen degree during dry periods when there might be less effective dilution by fresh water.

INFLUENCE OF WINDS UPON THE CIRCULATION IN THE BAY

In certain cases, for instance in estuaries of the fjord type, which might be quite well sheltered from the wind, the influence of winds upon the circulation can be neglected completely, especially if the tidal range is pronounced. In coastal plain estuaries and, similarly, in bar-built estuaries the wind, together with the tides, may dominate the water motions completely and obscure the effects of river flow.

Prevailing winds in the Biscayne Bay area are from southeast and east, the combined mean frequency of them being about 48 per cent. In Biscayne Bay the winds and, to a lesser extent the air pressure changes, will influence the water circulation and the mixing of water in the Bay. For practical reasons—the boat used for these studies was an open inboard workboat—field-trips were not made in rough

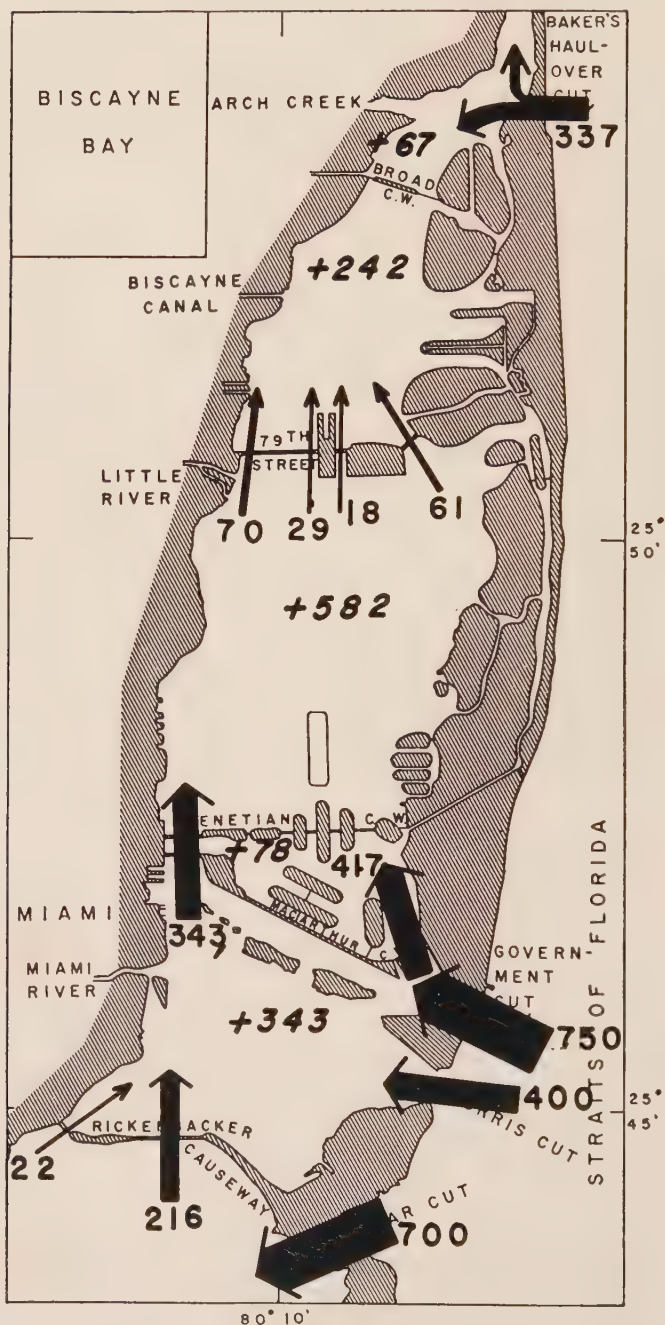


FIGURE 6. The volumes of water in 10^6 cubic feet per tidal cycle transported by the flood currents through different cuts; the thickness of the arrows indicates the amount of water.

weather. Thus, errors introduced by winds and changes in the air pressure were, we believe, mainly eliminated. This is indirectly shown by the fact that in most cases the tidal cycle data on salinity, oxygen, and currents were reversible. On the other hand, after a stormy period the water circulation pattern in the Bay may be rather different from a more normal pattern. This fact has affected the following study of the circulation of Biscayne Bay. Nevertheless, it is believed that under the above circumstances it is possible to neglect the effect of the meteorological influences upon the circulation in Biscayne Bay.

GENERAL TIDAL CONDITIONS IN BISCAYNE BAY

In the general hydrographic study of Biscayne Bay with which this survey was begun, the significance of the tidal changes was clearly indicated by all of the data. It was clear that all hydrographic and the pertinent biological, bacteriological, and chemical data should be corrected for tidal changes since only in this way could clear-cut correlations be shown. As shown in the first progress report (Hela, 1955) the tides in Biscayne Bay area are almost purely semidiurnal. This justifies the decision to cover on each station a period of only about 12 hours.

In Figure 6 two independent sets of water volumes are shown. With the arrows, the thickness of which indicates the amount of water, the different tidal prism volumes are given in 10^6 ft.³, brought into the Bay during a tidal cycle (cf. Minkin, 1949). It can be seen immediately that oceanic water is brought into the area of study mainly through Government Cut (750×10^6 ft.³) while through the other inlets the following volumes are brought: Norris Cut (400×10^6 ft.³), Baker's Haulover Cut (337×10^6 ft.³), and the bridges of Rickenbacker Causeway (238×10^6 ft.³). From the fact that only 178×10^6 ft.³ is transported under the four bridges of 79th Street Causeway it can be seen that the line of demarcation must be rather close to this Causeway.

Another set of water volume data, given in *italics*, is based upon the areas between the different causeways and upon the average tidal ranges. These values roughly correspond to the water transport values, but are slightly too low throughout the whole system since the water transport through the different cuts does not occur simultaneously. This was not taken into account as a correction when drawing the figure. Nevertheless, the order of magnitude of the different transport values may be obtained from Figure 6 with sufficient accuracy.

If one takes into consideration the whole of northern Biscayne Bay, the ratio $\frac{\text{Tidal Prism Volume}}{\text{Mean Discharge}}$ has a value of $\frac{13.0 \times 10^8 \text{ft.}^3}{0.54 \times 10^8 \text{ft.}^3} = 24$.

If only the region of Miami River, Government Cut, and Norris Cut is taken into account, the corresponding value would be, very approximately, 26.

THE HORIZONTAL SALINITY DISTRIBUTION

As a conservative element the salinity offers a unique possibility for the study of water circulation. In Figure 7 the mean salinity distribution is given in parts per thousand. In this figure and also in the following text only this most heavily polluted and hydrographically the most interesting part of Biscayne Bay is illustrated.

The salinity increases from some 5 parts per thousand in the mouth of Miami River to higher than 32.5 parts per thousand between the jetties of Government Cut. As to the shape of mean isohalines, there are three details to be pointed out. (1) The easternmost turn of the isohaline of 30 occurs northwest of Fisher Island. This shows where the main path of the draining fresh water, mixed in the Bay with the salt water, is to be found. (2) North of Rickenbacker and even of Venetian Causeway the path of the same isohaline is towards the north. Southwest of Fisher Island the same isohaline runs close to the waterfront of Coconut Grove and then south to station 804 (Main Bridge of the Rickenbacker Causeway). These courses indicate where some of the main paths of the ocean water are to be found. (3) The two isolated patches of water having a salinity higher than 25 parts per thousand just in front of the mouth of Miami River and close to the end of Main Ship Channel indicate that the last relatively unpolluted ends of salt water "jets" are found in this area where they are cut off from their source by the easterly fresh water intrusions from Miami River.

The same may be seen more clearly in Figures 8 and 9 which show the maximum and minimum salinities at each station during one tidal cycle. The maximum salinity corresponds, at least in a few cases but certainly not always, to the slack after flood. Similarly the minimum salinity roughly indicates the situation at the slack after ebb. Figure 10 shows the regional distribution of the tidal salinity range. The highest ranges are found between the Dodge Islands and the mouth of the Miami River. They also appear at the conjunction

of the Intracoastal Waterway with the flood currents flowing into the Bay through Baker's Haulover Cut, as shown in the first progress report (Hela, 1955). Ecologically it certainly would not be the same to note that the salinity at a certain station is on an average 25 parts

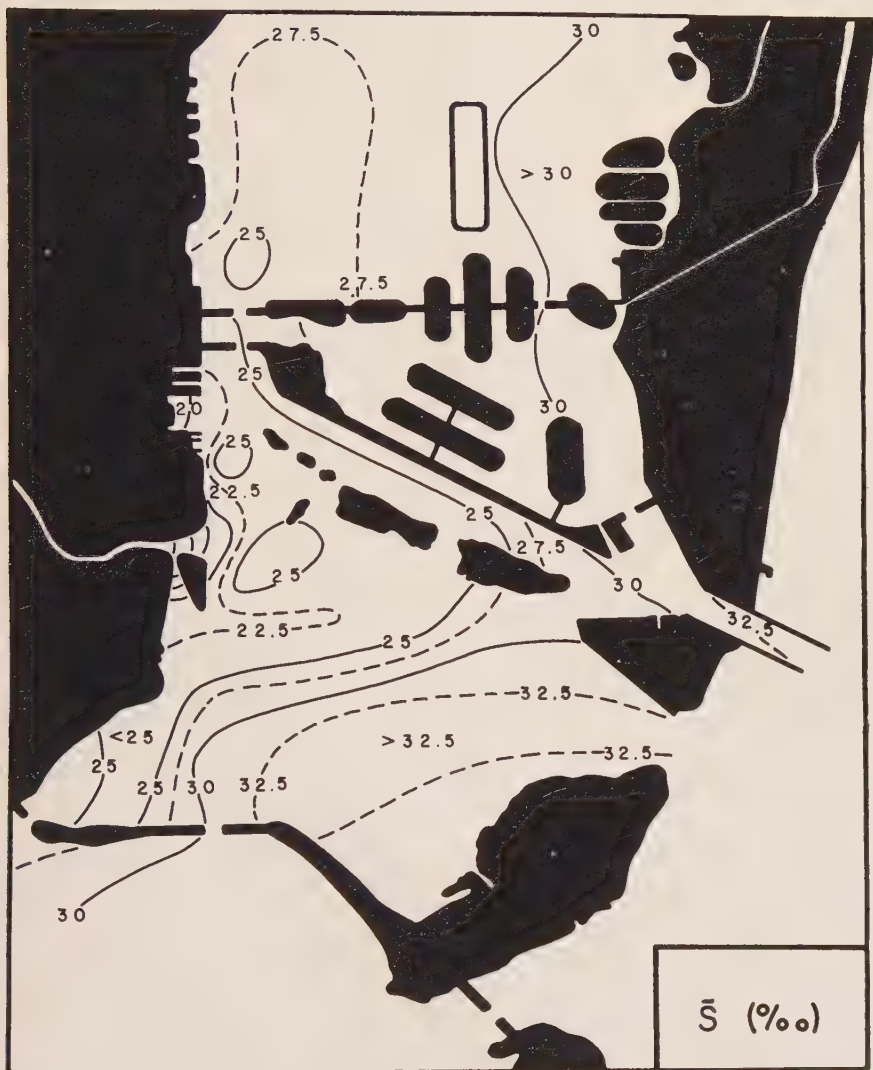


FIGURE 7. Average horizontal salinity distribution, in parts per thousand. At each station the water samples cover a period of one tidal cycle.

per thousand or that the salinity at certain station varies between 18.5 and 31.5 parts per thousand during every tidal cycle. Actually, the horizontal distribution of the absolute salinity range could be used as an indication for the areas with different intensities of flushing.

In contrast to the fairly regular pattern shown by the horizontal

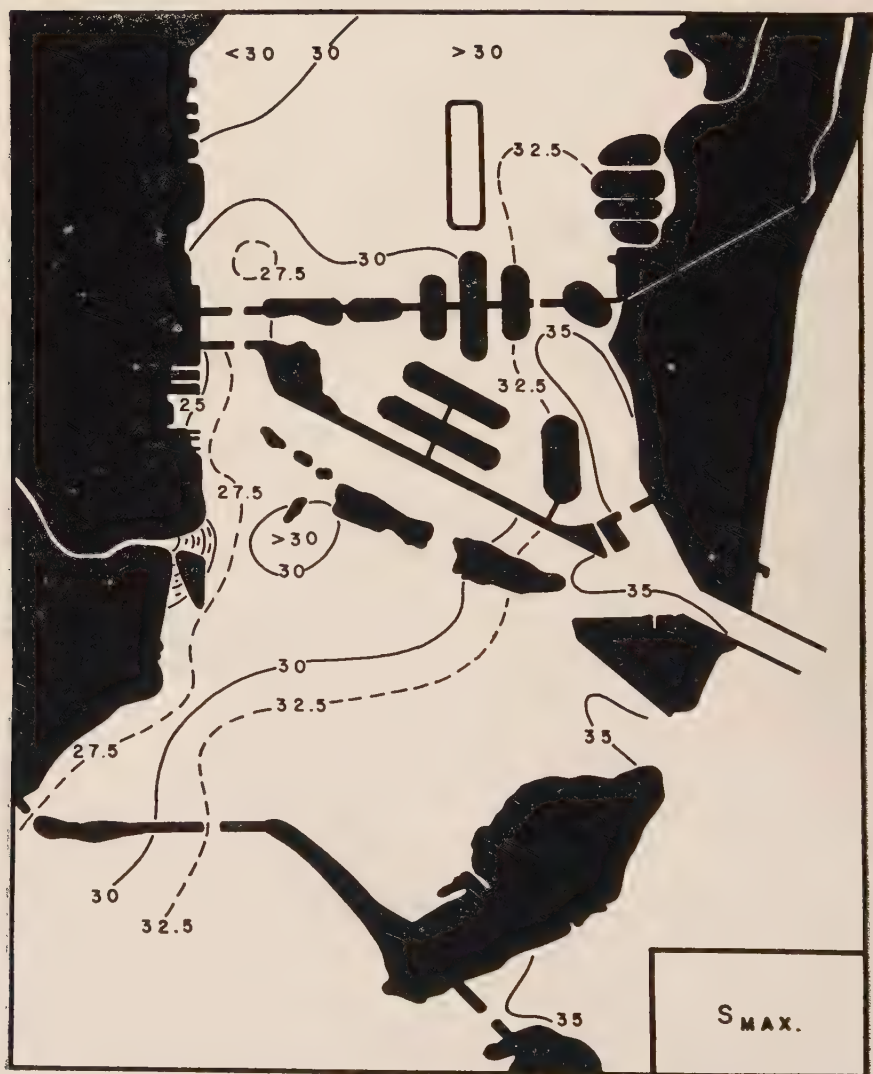


FIGURE 8. Horizontal distribution of maximum salinities of one tidal cycle.

salinity distribution, the temperature as a non-conservative element can not be used for similar studies. The experience from Biscayne Bay shows that in winter the Miami River water is colder than the ocean water. In summer the differences may be positive or negative and are small. No special attempts have therefore been made to study the horizontal distribution of temperature.

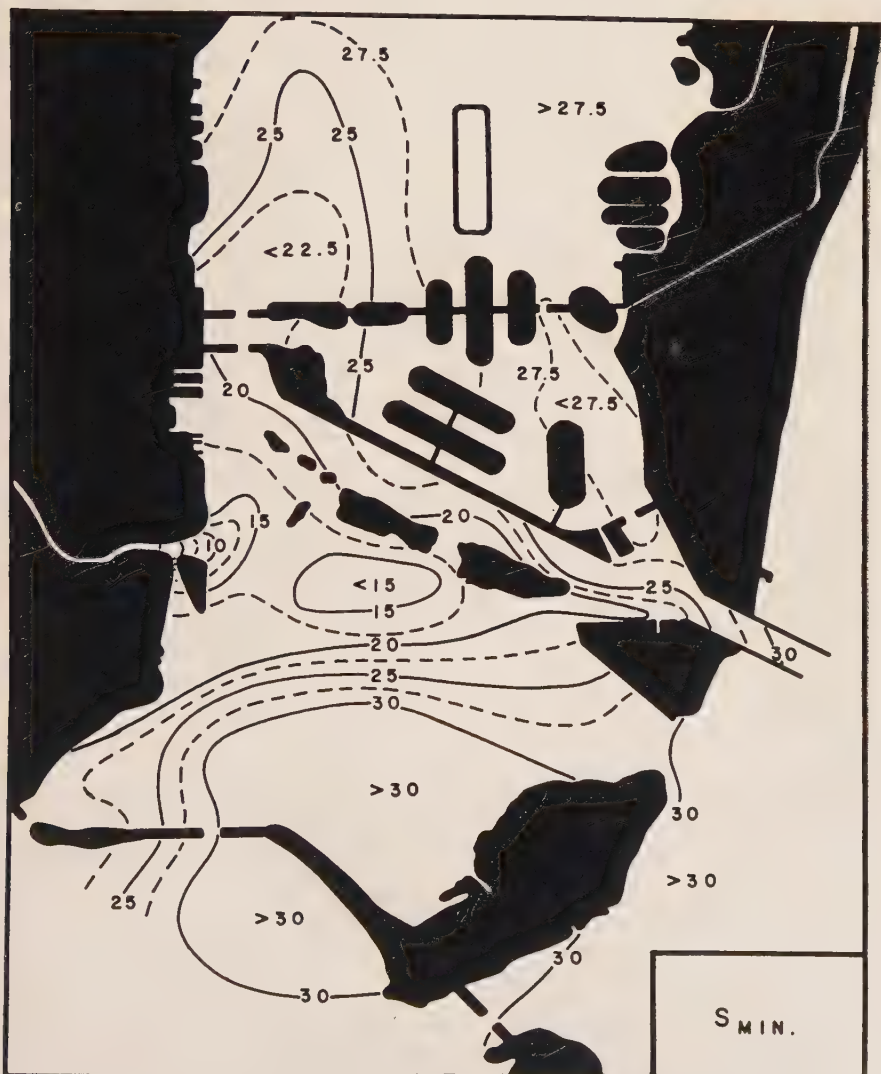


FIGURE 9. Horizontal distribution of minimum salinities of one tidal cycle.

HORIZONTAL DISTRIBUTION OF PER CENT SATURATION OF
DISSOLVED OXYGEN

Since the oxygen samples were not taken simultaneously and thus not under the same temperature conditions, and since even the salinity varies from station to station and from time to time the

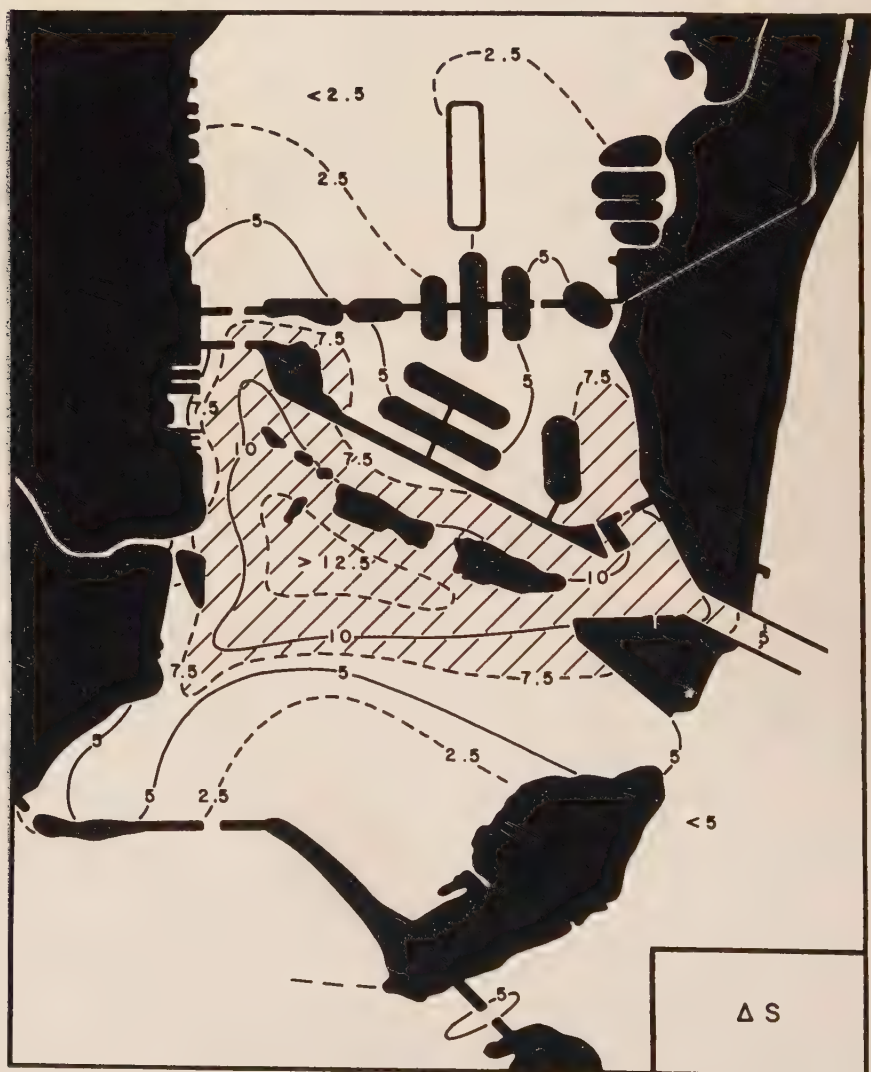


FIGURE 10. Horizontal distribution of tidal salinity range.

per cent saturation of dissolved oxygen is more suited for distribution studies than the absolute amount of dissolved oxygen.

In Figure 11 the mean values are given for the per cent saturation of dissolved oxygen. In general the per cent saturation was found to

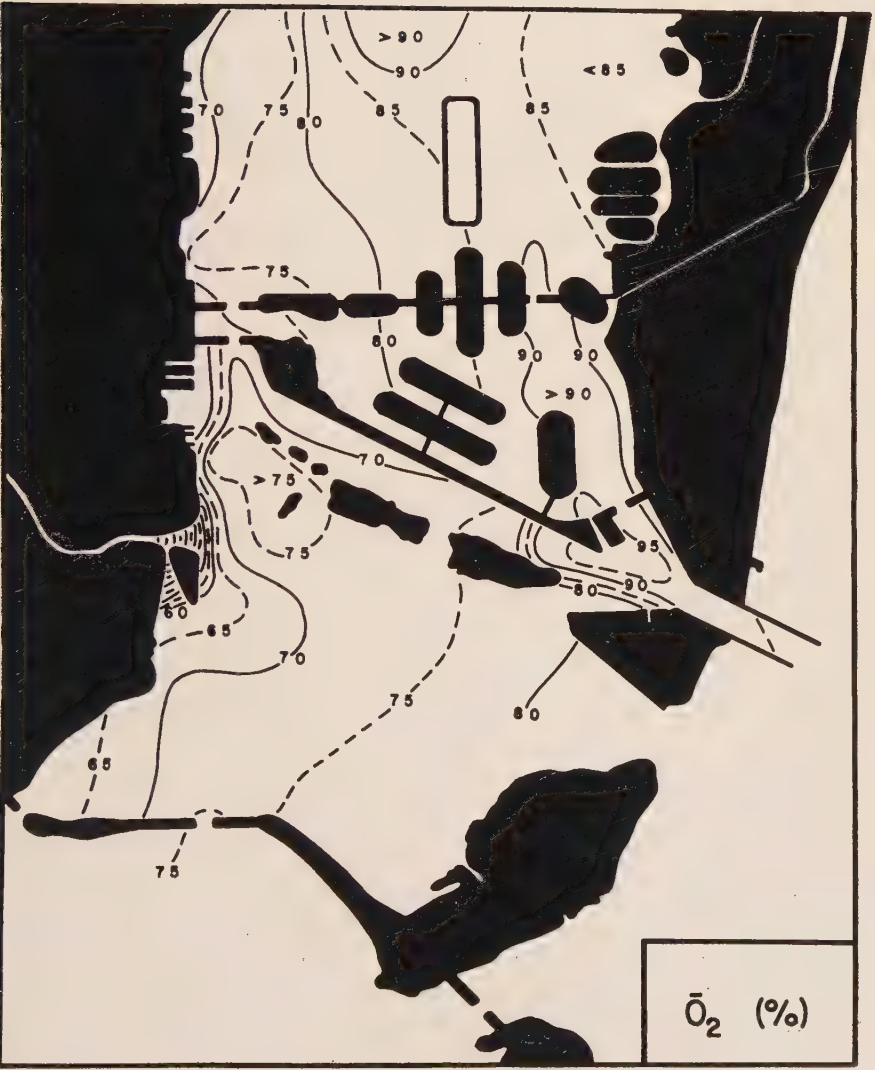


FIGURE 11. Average horizontal distribution of per cent saturation of dissolved oxygen. At each station the water samples cover a period of one tidal cycle.

be higher than expected (see Figure 5). There are two reasons for the relatively high oxygen values: (1) the discharge of Miami River was in 1954 much higher than in 1949 (see Figure 4); (2) this part of the study was performed in June through August (the same way as the study of 1949, in May through August). During the winter season the increased Miami population undoubtedly will push the limits of pollution much farther.

Except for the Miami River mouth and immediate vicinity, where conditions are septic, oxygen saturation values well above the 40 per cent level are generally found throughout the Bay. The easternmost traces of the less oxygen rich water are found west of Fisher Island. Actually, the rather limited extension of the area of pollution contributes to the nuisance brought about the pollution. If the raw sewage were evenly distributed throughout Biscayne Bay, it would cause practically no nuisance at all.

The effect of oxygen rich water along the western shoreline of Miami Beach is very pronounced. Per cent saturation values higher than 90 per cent at the northernmost edge of the chart show the closeness of the non-polluted Bay area south of the 79th Street Causeway. Relatively low oxygen content north and northwest of Virginia Key is believed to indicate the poorly developed circulation of this shallow area. The pool of water with relatively high oxygen content in front of Miami downtown area is quite evident.

The distributions of maximum and minimum per cent saturation values of dissolved oxygen are given in Figures 12 and 13. At the northernmost edge of the map over saturated water appears in conjunction with the north and south movement of the line between the southern polluted and northern non-polluted areas. It is interesting to note that maximum oxygen saturation is well above 90 per cent not more than 200 yards from the Miami downtown waterfront, while the minimum oxygen saturation of 60 per cent or less reaches Fisher Island.

The tidal range of per cent saturation of dissolved oxygen is seen in Figure 14. The resemblance to the corresponding salinity pattern is remarkable, except for the area north of the proper polluted region.

As can be seen from Figure 15, there seems to exist in this area a linear relationship between the numerical values of salinity and the per cent saturation of dissolved oxygen:

$$[O_2] = 2.7 \times [\bar{S}]$$

This relationship is a natural one because the concentration of river

water, C_r , within any increment of the estuary water is determined approximately by the relationship

$$C_r = \frac{\sigma - S}{\sigma}$$

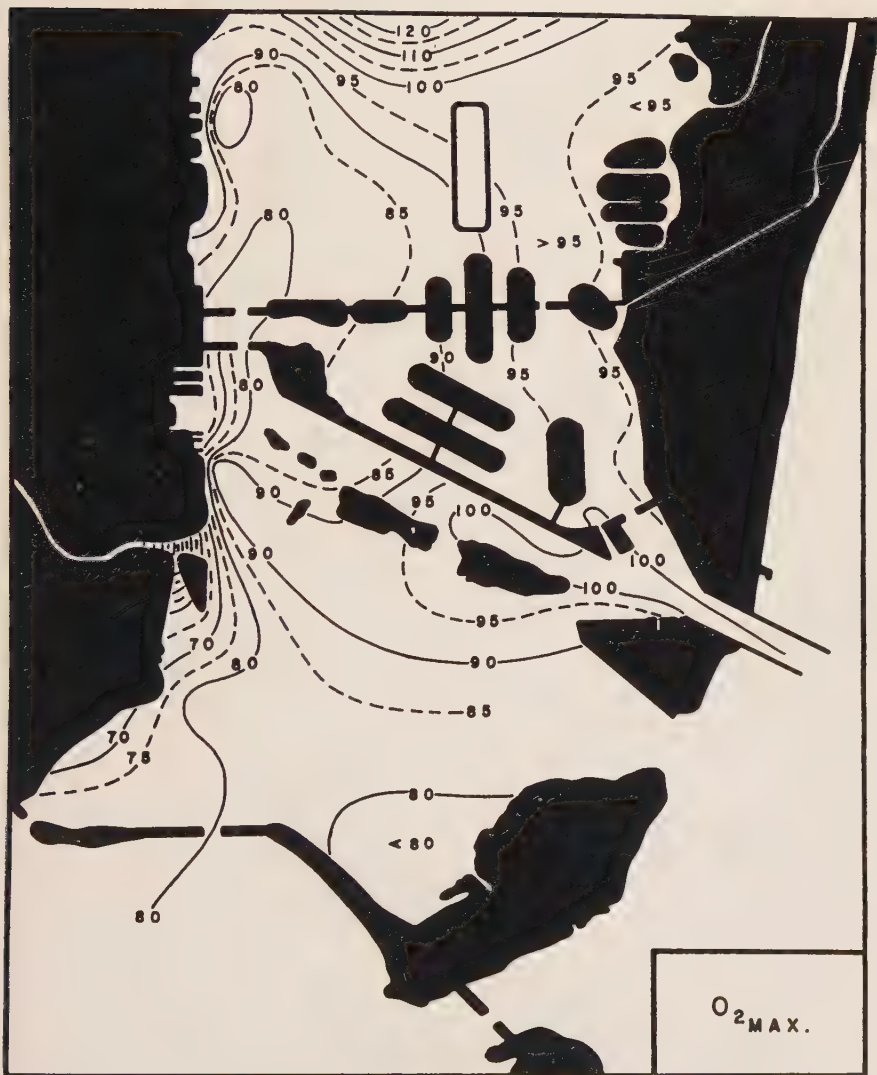


FIGURE 12. Horizontal distribution of maximum values of per cent saturation of dissolved oxygen.

where σ is the base salinity of ocean water and S is the observed salinity of the estuarine water within the increment. Since in Biscayne Bay the river water is characterized by the lack of dissolved oxygen, while in pure ocean water the saturation of dissolved oxygen must

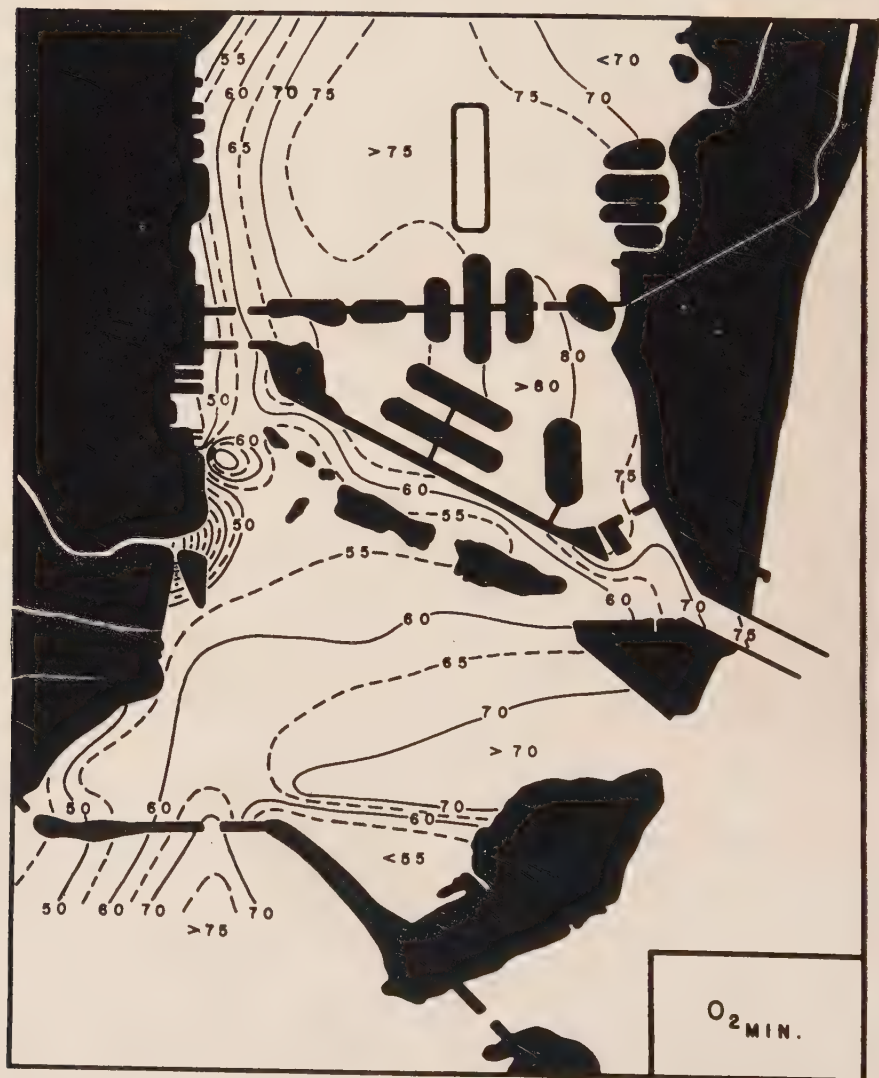


FIGURE 13. Horizontal distribution of minimum values of per cent saturation of dissolved oxygen.

be at least 100 per cent,

$$|O_2| \sim 1 - C_r = 1 - \frac{\sigma - S}{\sigma} = \frac{S}{\sigma}$$

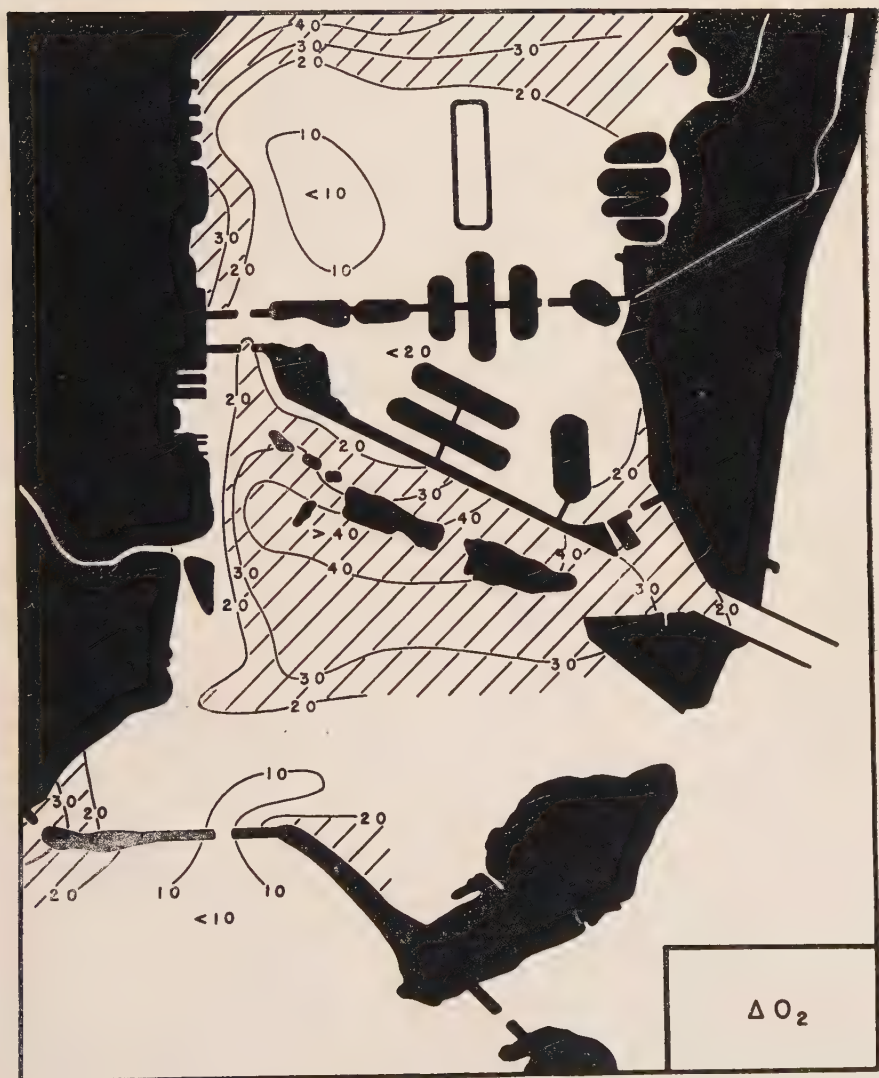


FIGURE 14. Horizontal distribution of range of per cent saturation of dissolved oxygen.

The above empirical relationship would give for the base salinity an approximate value of 37 parts per thousand which does not deviate too much from the correct values.

Since there are deviations from the above relationship, it is worthwhile drawing the regional distribution of the numerical ratio $|\bar{O}_2| : |\bar{S}|$ (Figure 16). As to the section south of MacArthur Causeway, the change (cf. Figures 10 and 14). The ratio is lower than 2.7 where the water exchange is at its minimum. Unfortunately, between MacArthur and Venetian Causeways the number of stations is not high enough to give any proof of the correctness of the schematic drawing. North of the Venetian Causeway again it is seen that the intensive water exchange affects the above ratio in a favorable way.

HORIZONTAL DISTRIBUTION OF PER CENT SATURATION OF DISSOLVED OXYGEN AT DIFFERENT TIDAL PHASES

Since the diagrams of maximum and minimum salinities (see Figures 12 and 13) do not refer directly to any tidal phases, in Figures 17 through 20 the distribution of per cent saturation of dissolved oxygen at different tidal phases is given. The time 0^h (see Figure 17)

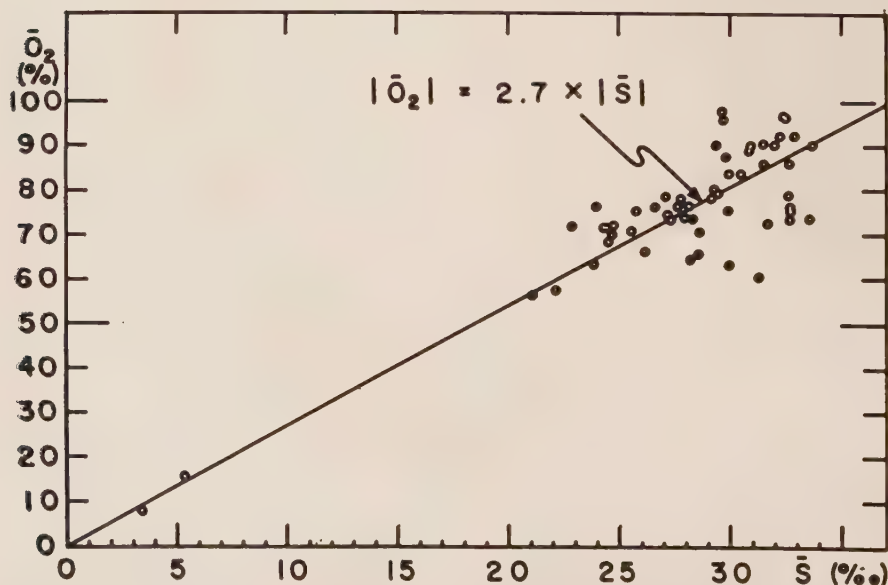


FIGURE 15. Relationship between the numerical values of salinity and the per cent saturation of dissolved oxygen.

refers to the moment of maximum flood between the jetties of Government Cut. The time 3^h (see Figure 18) shows the saturation 3 lunar hours later or, roughly, at the moment of slack after flood when, at least in several sub-areas, the oxygen content is at its maximum. The time 6^h (see Figure 19) approximately corresponds to the

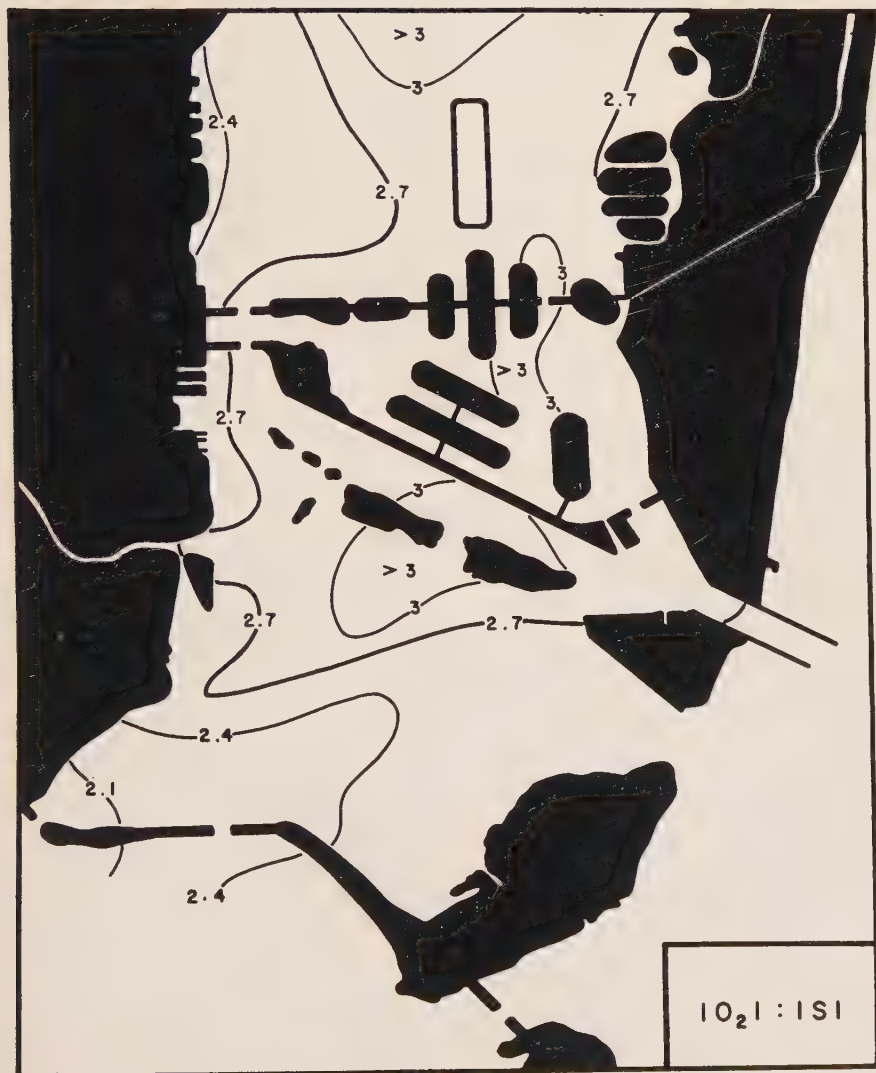


FIGURE 16. Regional distribution of the ratio between the per cent saturation of dissolved oxygen and the salinity.

moment of maximum ebb between the jetties. And, finally, the time 9^h (see Figure 20) shows the oxygen distribution three lunar hours later, that is, at the moment of slack after ebb when the oxygen content is supposed to be at its minimum, at least in several cases.

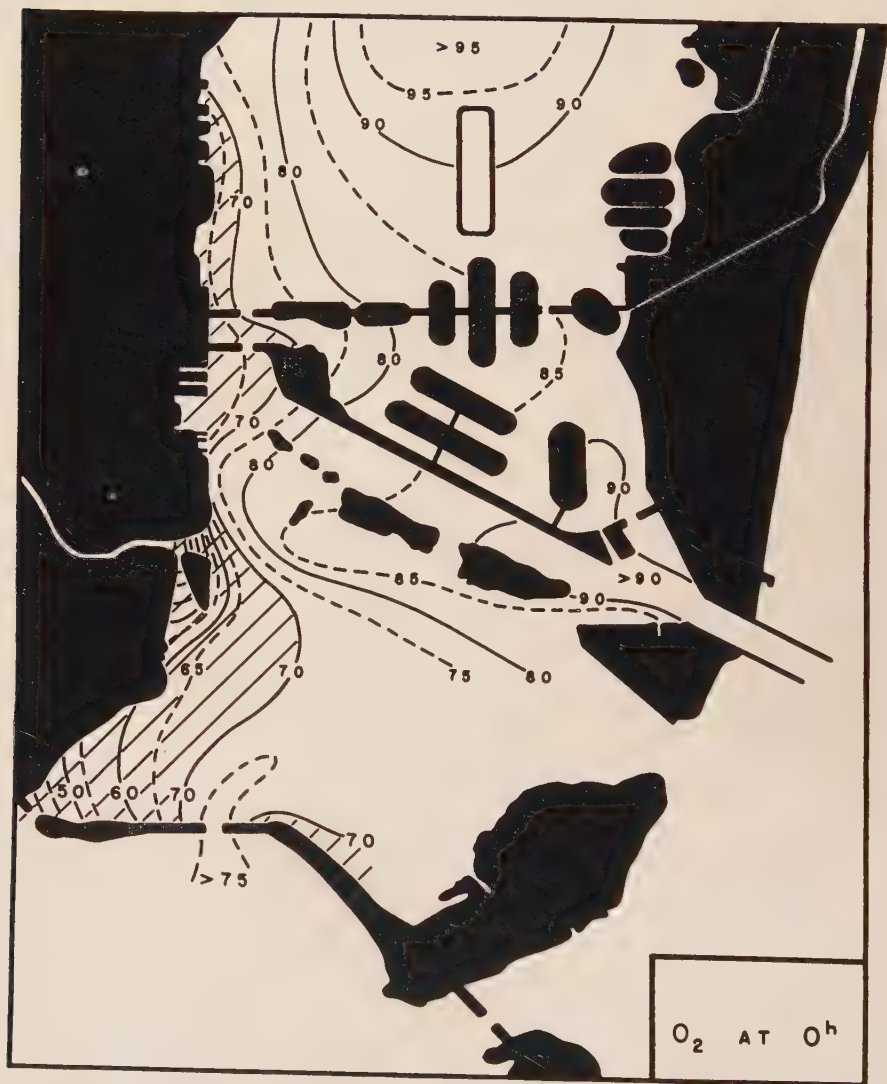


FIGURE 17. Horizontal distribution of per cent saturation of dissolved oxygen at 0^h (when the maximum flood is observed between the jetties of Government Cut).

Several interesting features can be seen from these figures. The ocean water intrusion towards the Miami downtown shoreline is already cut off from its source, before the slack after flood, by the fresh water which runs from Miami River towards Fisher Island. The oxygen rich water along the western waterfront of Miami Beach,

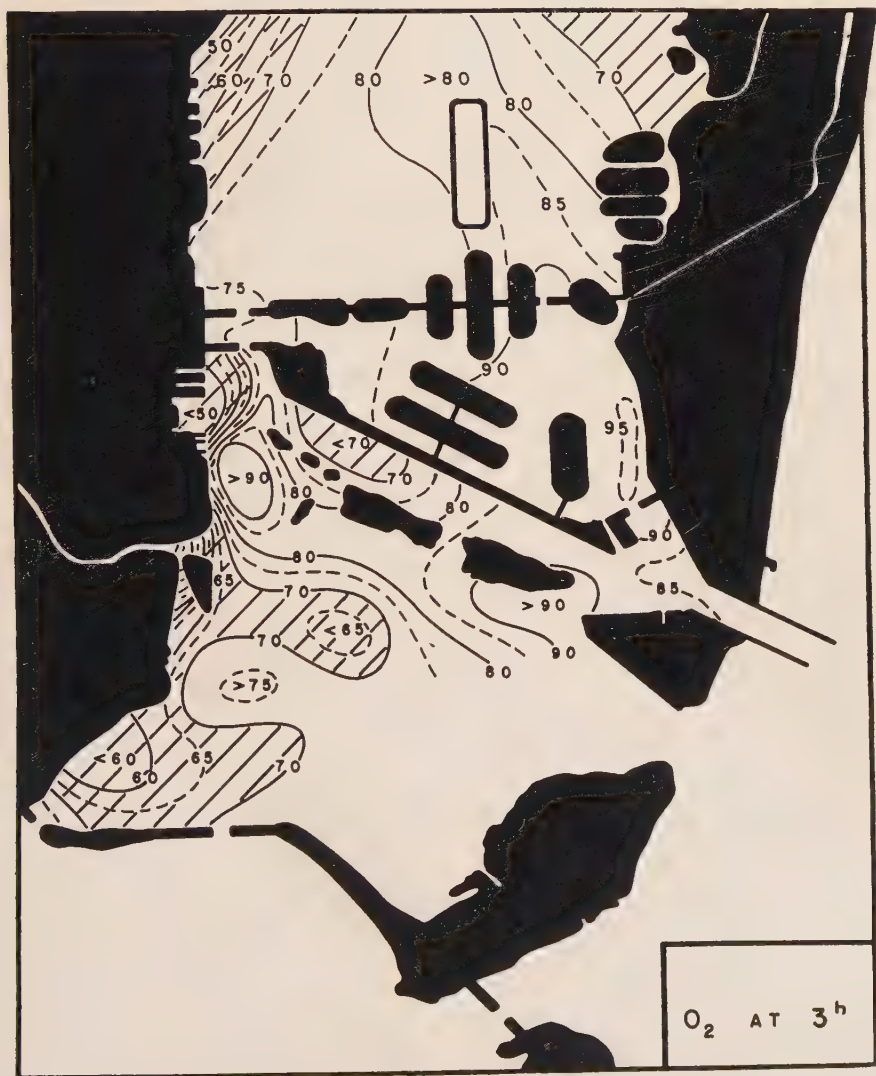


FIGURE 18. Horizontal distribution of per cent saturation of dissolved oxygen at 3^h lunar time.

most pronounced 6 hours after the maximum flood, has its immediate origin in the non-polluted area close to the 79th Street Causeway. The same facts can be seen still more clearly from the Figures 21 and 22 which show in lunar time the appearance of maximum and minimum per cent saturations of dissolved oxygen. Along the Main



FIGURE 19. Horizontal distribution of per cent saturation of dissolved oxygen at 6^h lunar time.

Ship Channel and south of the Dodge Islands the maximum oxygen content is encountered 0 to 3 hours after the maximum flood, but along the western waterfront of Miami Beach the corresponding maximum does not appear until 6 to 9 hours after the maximum flood. Minimum oxygen content is found in the last mentioned area 9 to

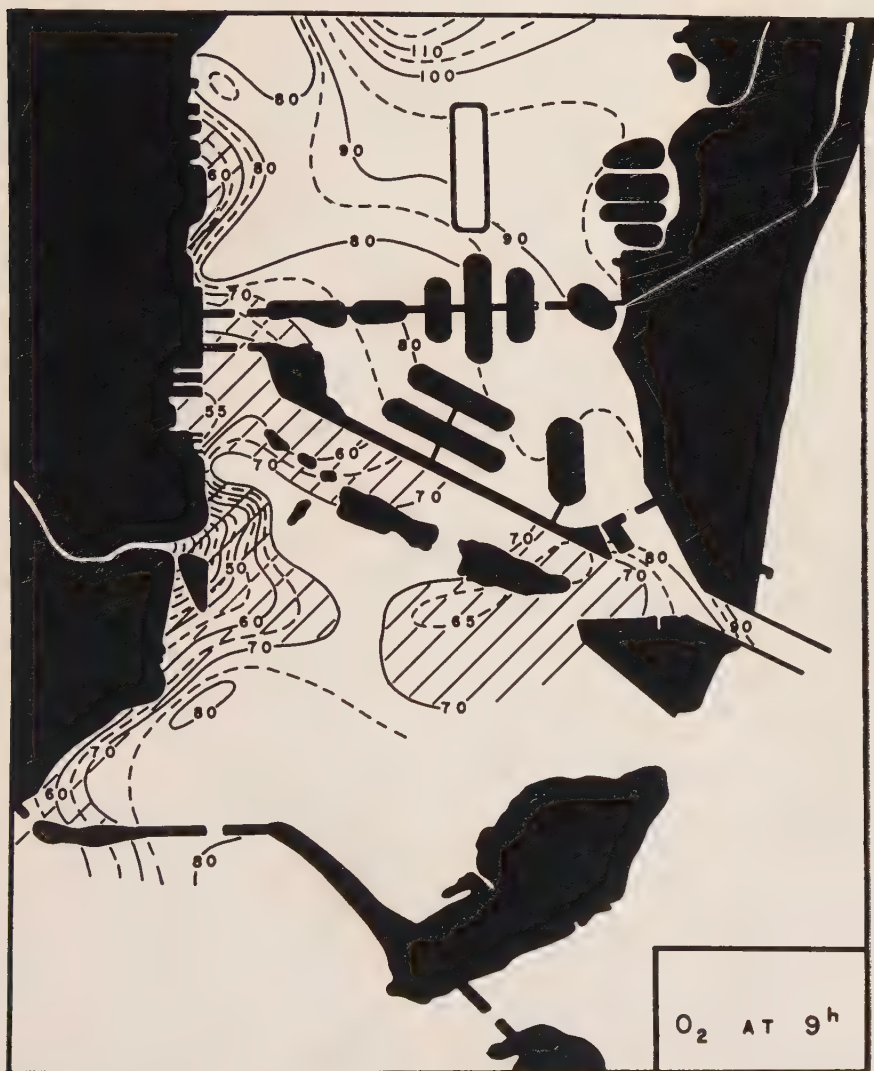


FIGURE 20. Horizontal distribution of per cent saturation of dissolved oxygen at 9^h lunar time.

12 hours after the maximum flood, while the minimum appears in and around the Main Ship Channel 6 to 9 hours after the maximum flood.

This can be explained only in the following way. The most heavily polluted waters are drained through the Government Cut between

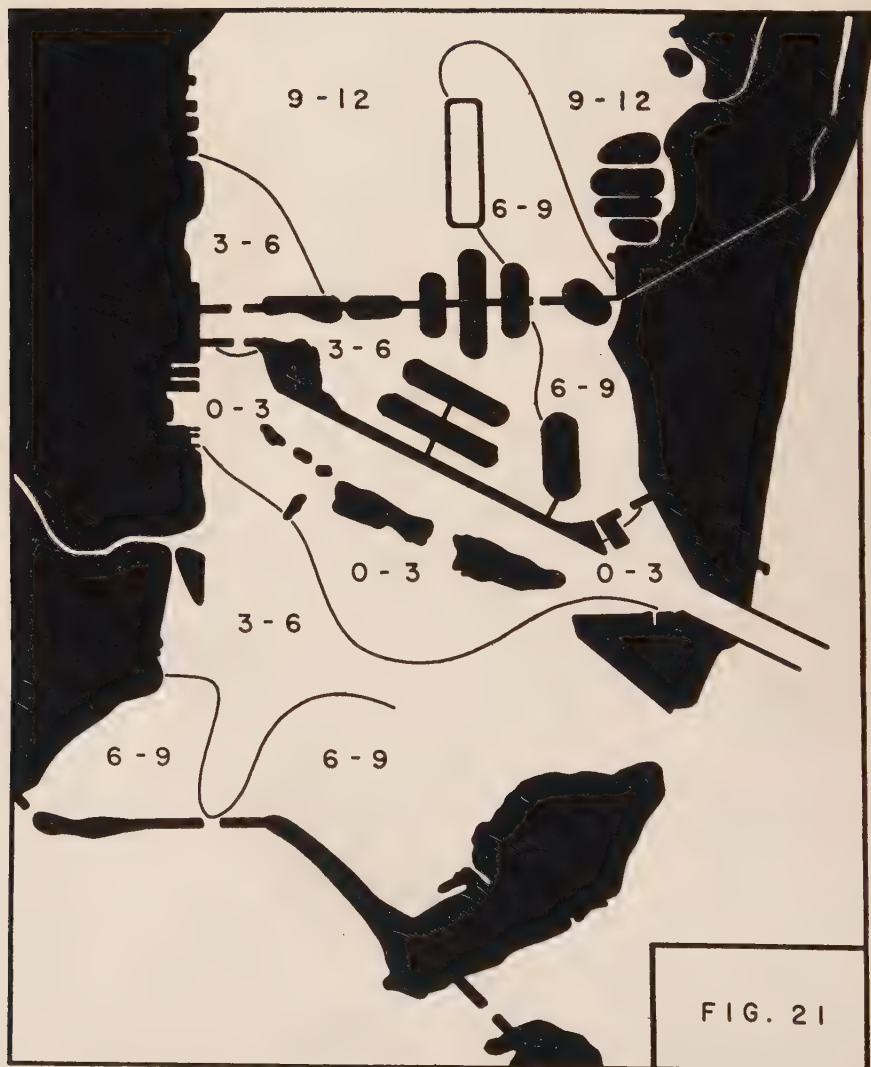


FIGURE 21. Regional distribution of the time of appearance of maximum of per cent saturation of dissolved oxygen.

6 and 9 o'clock (lunar time), that is, in connection with the last part of the ebb (Figure 22). The minimum oxygen contents are found along the western shoreline of Miami Beach between 9 and 12 o'clock. This means that some of the water drained from the most

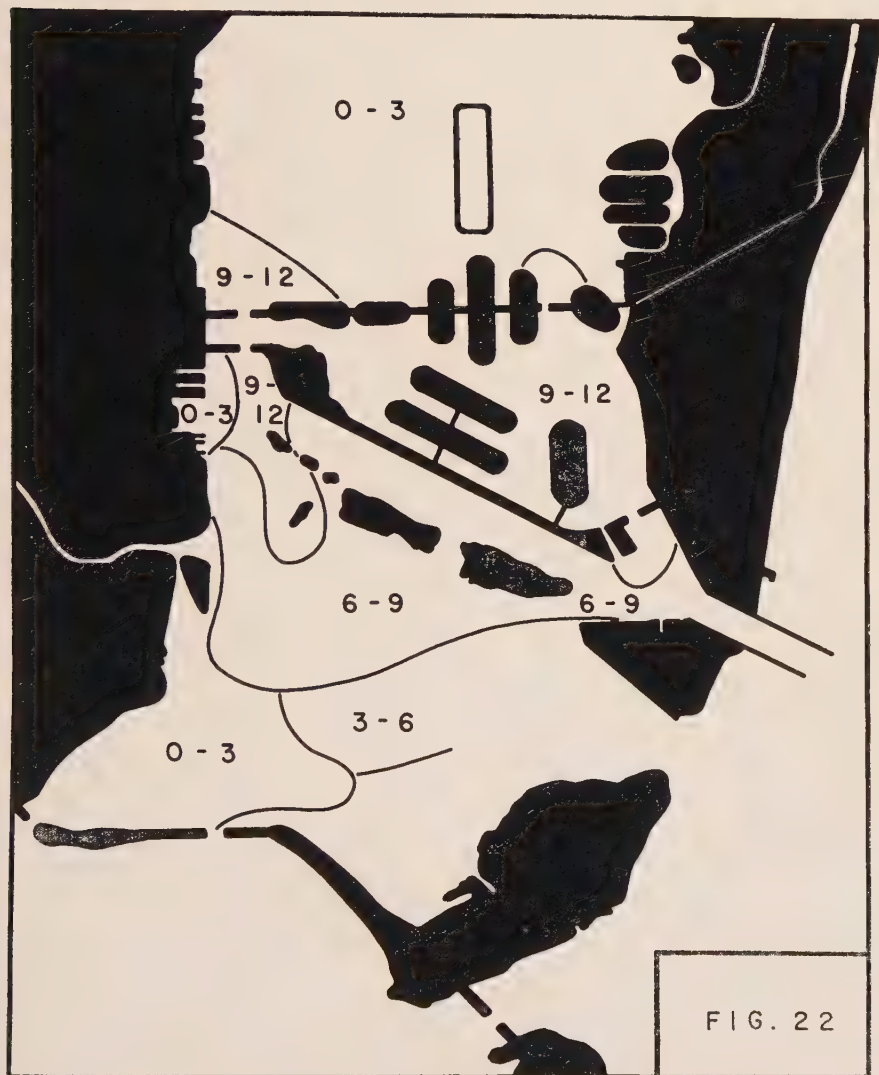


FIGURE 22. Regional distribution of the time of appearance of minimum of per cent saturation of dissolved oxygen.

TABLE 2
MEASURED CURRENTS (COMBINED WITH TIDAL OBSERVATIONS OF SALINITY)

	F _{max}	1	2	3	4	5	E _{max}	6	7	8	9	10	11	
	0			E _o							F _o			
1954; June 17														
16	0	0	0	0	S	SSE	SSE	0.7	N	0.8	N	N	0.7	1.2
17	0	0	0	SSE	SSE	1.1	0.7	0.7	N	1.0	NE	N	0.7	1.1
20	SSE	S	S	0.1		NNE	N	0.9	1.0		NNE	NNE	0.7	1.0
603	NW			SSE	ESE	ESE	ESE	0.7	NNE	1.0	NNW	NNW	0.8	0.8
604	WNW	WNW	0	0.2	ESE	ESE	ESE	0.8	ESE	1.0	WNW	WNW	0.8	1.0
703	ENE	ENE	ENE	ENE	ENE	ENE	ESE	1.6	ENE	1.2	ENE	ENE	0.9	1.6
704	ENE	ENE	ENE	ENE	ENE	ENE	ENE	1.0	ENE	1.0	ENE	ENE	0.8	1.0
705	S	S	S	S	0		N	0.6	N	0.8	NNE	NNE	0.6	0.8
706	S			0			NE	0.6	NE	1.0	NNE	NNE	0.9	1.0
1954; July 2														
21	SW	S	S	S	SSE	SSE	NNW	0.6	N	0.8	N	N	0	0.8
22	S	S	SW	SW	SSW	SSW			N	0.6	N	N	0	0.9
24	SW	S	SW	SW	SW	SW		0	S	0.7	E	0	0	0.8
61	0	SW	SW	SW	SSE	SSE			N	0.2	0.6	0	0	0.7

	F _{max}	1	2	3	E _o	4	5	E _{max}	6	7	8	9	F _o	10	11
801		S 0.7	S 0.9	S 0.8	S 0.7	S 0.8	0			S 0.4	S 0.7			SW 0.6	S 0.8
802	S 0.2		S 0.8	S 0.7	S 0.7	S 0.7		SW 0.6			SW 0.7		SW 0.7		0
804	0		0	0.1	0	0		N 0.7		N 0.6			0	0	0
1954; July 9															
51	NNE 0.5		0	0				SSW 0.6		0				NNE 0.6	0
52		NNE 0.7				SSW 0.3		SSW 0.4		0		N 0.2		NNE 0.7	
55	N 0.8		W 0.7	0.8	S 0.7			0			N 0.7		N 0.8		N
401	N 0.7		NE 0.7	0		0		0		0	0		N 0.7		N
402	NNE 0.7		W 0.4	0.4	SSW 0.7			SSW 0.7					NNE 0.7		NNE
403		NW 0.4	0	0		SSW 0.3		0		0			NE 0.6		NNE
501	N 0.7		0	0	SSW 0.7			S 0.7		0			N 0.8		N
1954; July 21															
804W	0		0	0		0		NE 0.8		NE 0.7	NNE 0.7			0	0
804			SxW 0.7	0	ENE 0.6	0		ENE 0.6		NE 0.8	NNE 0.7			NNE 0.7	N
804E			0	0	S 0.8	S 0.8		0		N 0.8		N 0.8		NxW 0.7	0
1008W	SSW 1.4		SxW 1.3	NNE 0.9	NNE 1.0	NNE 1.0		NNE 1.1		NE 0.9			NNW 0.6		SSW 0.8
1008	SSW 1.0		SxW 0.7	N 1.2	NNE 1.4	NNE 1.4		1.6		NE 1.3			NNE 0.7	SW 0.9	
1008E	SSW 1.5		S 0.9	NNE 1.0	NNE 1.4	NNE 1.4		NNE 1.6		NE 1.2			NNE 0.7	SW 1.4	

TABLE 2 (Continued)
MEASURED CURRENTS (COMBINED WITH TIDAL OBSERVATIONS OF SALINITY)

	F _{max}	1	2	3	4	5	E _{max}	6	7	8	9	10	11
1954, July 26 & 30													
41	0	0	0	0	0	SW 1.2	S 0.8	S 0.8	S 0.9	S 0.9	S 0.8	SWxS 0.8	1.2
43	0	0	0	0	0	NE 0.8	NEXE 0.6	SW 0.6	NEXE 0.7	SW 0.6	SWxS 0.8	0.8	0.8
44	0	0	0	0	0	NEXE 0.6	NEXE 0.6	0	0	0	0	0	0.7
82	0	0	0	0	0	N 0.9	NEXN 0.9	S 0.8	N 0.8	S 0.7	S 0.8	0	1.1
102	0	0	0	0	0	NE 0.9	NE 0.9	SW 0.6	NE 0.9	SW 0.6	SW 0.6	0	1.0
103	W 2.7	0	0	0	0	E 2.7	E 2.1	W 2.1	E 1.8	W 2.1	W 2.1	0	3.3
August 4						E 0.6	E 0.6	0	0	0	0	0	0.8
203W						SSW 0.7	SSW 0.7	0	SxW 0.6	0	0	0	0.8
203						S 0.8	S 0.8	0	0	0	0	0	0.8
203E						N 0.8	N 0.8	0	0	0	0	0	0.8
206W						0	0	0	0	0	0	0	0.8
206						NE 0.7	NE 0.7	0	0	0	0	0	0.8
206E						N 0.7	N 0.7	0	0	0	0	0	0.8
August 11						0	0	0	0	0	0	0	0.8
608						E 1.0	E 0.8	E 0.8	E 0.8	E 0.8	E 0.8	W 1.3	1.3
608N						E 1.2	E 1.6	E 1.1	E 1.1	E 1.1	E 1.1	S 1.5	1.6

	F _{max}	1	2	3	E _o	4	5	E _{max}	6	7	8	9	F _o	10	11	
710	SE 1.0	0			E 0.8	E 0.7		E 0.9	E 0.6				ENE 0.8			ExS 0.8
701SE	W 0.7	0		E 0.8		SE 0.8		S 1.0	SE 0.8				0		W 0.7	
713N	WxS 1.8	WxS 0.8	E 1.2		E 1.3	E 1.3		E 1.3	E 1.0				W 1.0	WxS 1.6		
713	W 1.2	W 0.8	E 1.0		E 1.1	E 1.2		E 1.2	E 1.0				W 0.9	W 1.4		
713S	W 1.3	W 0.7	E 0.9		E 1.0	E 1.0		E 1.0	E 0.8				W 0.9	W 1.4		
August 13																
93	NxW 1.1	NxW 0.9	S 0.9		S 1.4	S 1.2		S 1.4	S 1.3		SE 0.7			N 1.6		N 1.6
98W	NNW 1.0	0	0		SxS 1.2	SxS 1.2		SxS 1.5	SxS 1.2		SE 0.9			NNW 1.4		NW 1.4
98E	NW 1.1				S 1.2	S 1.2		S 1.7	SxS 1.2		SxS 0.8			NW 1.4		NW 1.4
99		NNW 1.0	0	SSW 1.1		SW 1.4		SE 1.3	SE 1.2			N 1.0		NW 1.6		NNW 1.4
611N	W 1.8	WSW 0.7	1.6		E 1.6	E 1.8		E 1.6	E 1.0		E 1.0		W 1.8	W 2.1		W 2.1
611	W 2.2	SW 1.0	2.1		E 2.1	E 2.9		E 3.1	E 1.9		E 1.9		W 3.2	W 3.2		W 3.2
611S	W 1.1	W 0.8	1.3		E 1.3	E 1.8		E 1.5	E 1.0		E 1.0		W 1.8	W 1.8		W 1.8
August 20																
55W		N 1.0	0.7	W 0.7	SW 1.0	SW 1.0		SxW 1.0	SxW 0.7		N 0.7		N 1.2	N 1.3		N 1.3
55		N 1.0	0.7	W 0.7	SW 0.6	SW 0.6		S 0.8	SxW 0.7		0		NxS 1.0	N 1.4		N 1.4
55E		N 1.1	0	0	SxW 0.8	SxW 0.8		S 0.9	0		N 0.7		N 1.0	N 1.4		N 1.4
501W		N 1.0	1.0	W 1.0	SW 0.8	SW 0.8		SSW 0.8	S 0.8		0		NxS 1.2	NxS 1.3		NxS 1.3
501		N 1.0	0.7	W 0.7	SW 1.0	SW 1.0		SSW 1.2	SxW 0.8		NxS 0.8		NxS 1.2	NxS 1.4		NxS 1.4
501E		NW 1.0		W 0.8	SSW 1.0	SSW 1.0		SSW 1.0	SxW 0.9		NxS 0.7		NxS 1.2	NxS 1.2		NxS 1.2

heavily polluted area of the Bay comes to a stop in the Government Cut and is brought back by the first part of flood northward along the western edge of Miami Beach. During the latter part of the flood, the relatively pure ocean water with highest oxygen content almost reaches the shoreline of Miami (see Figure 21). The waters with highest oxygen content, found along the western waterfront of Miami Beach between 6 and 9 o'clock, are transported from the non-polluted area between Venetian Causeway and 79th Street Causeway.

MEASURED CONTENTS AND THE HOURLY CHANGES OF SALINITY

Tidal currents (Table II) were measured by means of the von Arx Current Meter simultaneously with tidal observations of salinity. All the most apparent water movements are found to be related to tidal motion with tidal currents of about 0.5 to 3 knots. The maximum speeds of current are, roughly, the following: Baker's Haulover Cut 2.8 to 4.7 knots; Government Cut 2.5 to 3.7 knots; Bear Cut 1.3 to 2.0 knots; Miami River, the Venetian Causeway bridges, and MacArthur Causeway, the eastern half of Main Ship Channel, Norris Cut, and also the northernmost tip of the Bay, about 1.5 knots; other bridges of Rickenbacker Causeway, bridges of the 79th Street Causeway, and the open Bay less than 1.0 knot, averaging 0.5 knots. In the area between Venetian Causeway and 79th Street Causeway the currents seem to be influenced by the winds.

Finally, all of the measured currents, in knots, were plotted (Figures 23-34), each of them showing the current situation during one lunar hour. The time 0^h, once more, refers to the time of maximum flood between the jetties of Government Cut.

The principal difficulty in the following interpretation, and similarly in all corresponding efforts, is due to the fact that simultaneous observations cannot be performed in a sufficient number of places. Therefore, meteorological and hydrological changes must affect the results. Fortunately the influence of the winds seemed here to be rather restricted, nor did the discharge vary greatly.

An effort has been made to compute and to plot the corresponding hourly changes of surface salinity on the same maps with the currents. Increasing salinity in a certain area means water movement from an area where the salinity during the previous hour was higher, and decreasing salinity correspondingly indicates movement of water from an area with lower salinity towards an area with higher salinities, since the effect of mixing cannot achieve salinity changes of the order of

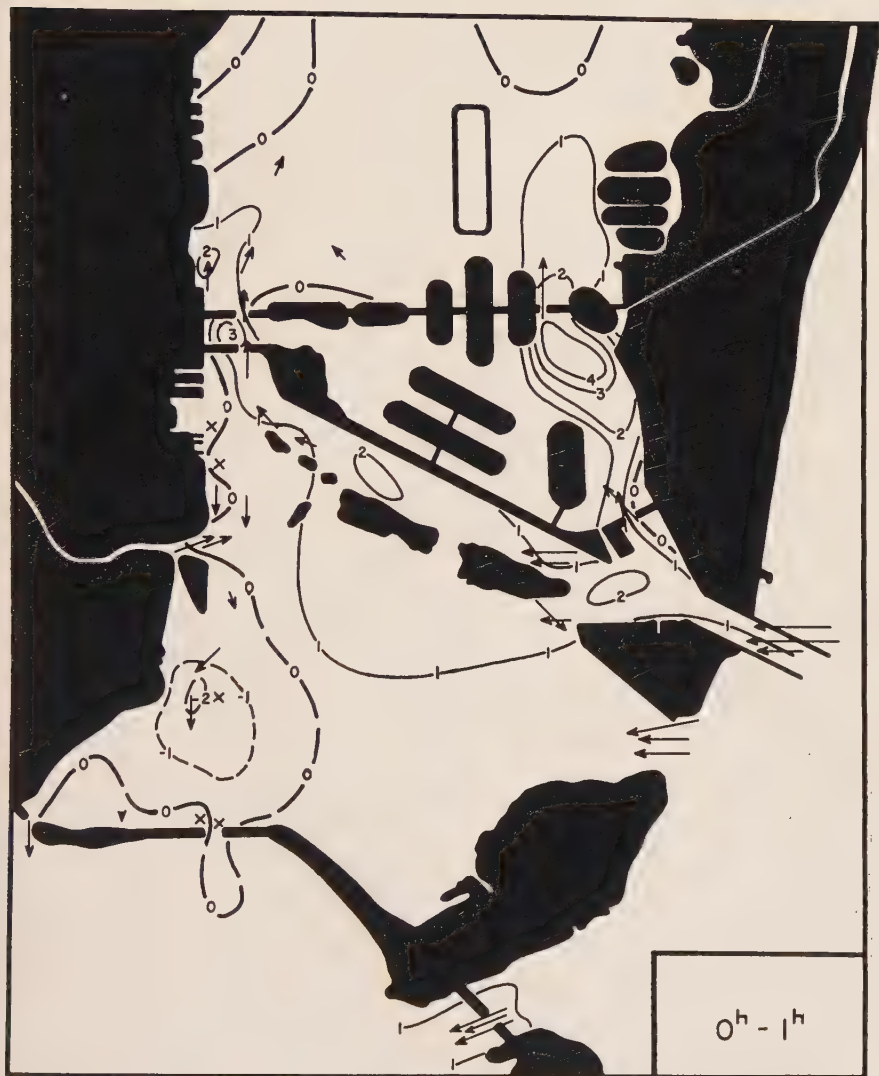


FIGURE 23. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

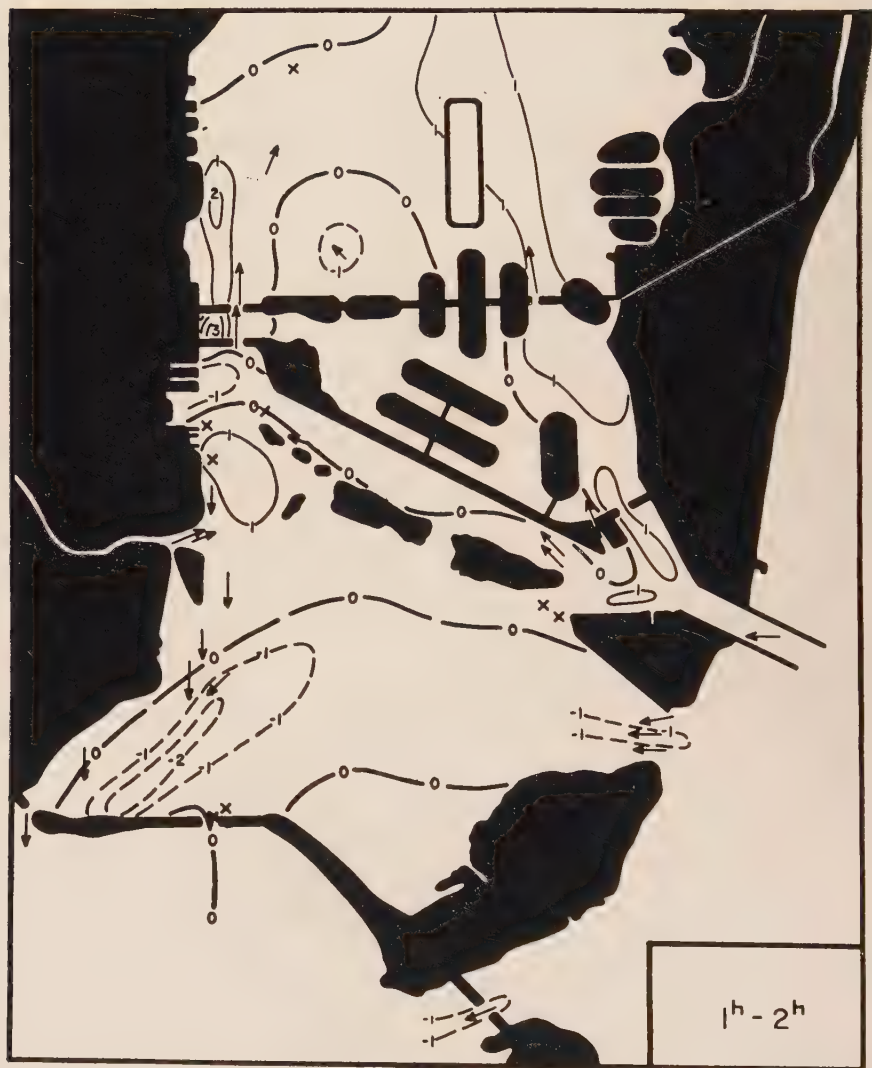


FIGURE 24. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.



FIGURE 25. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.



FIGURE 26. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

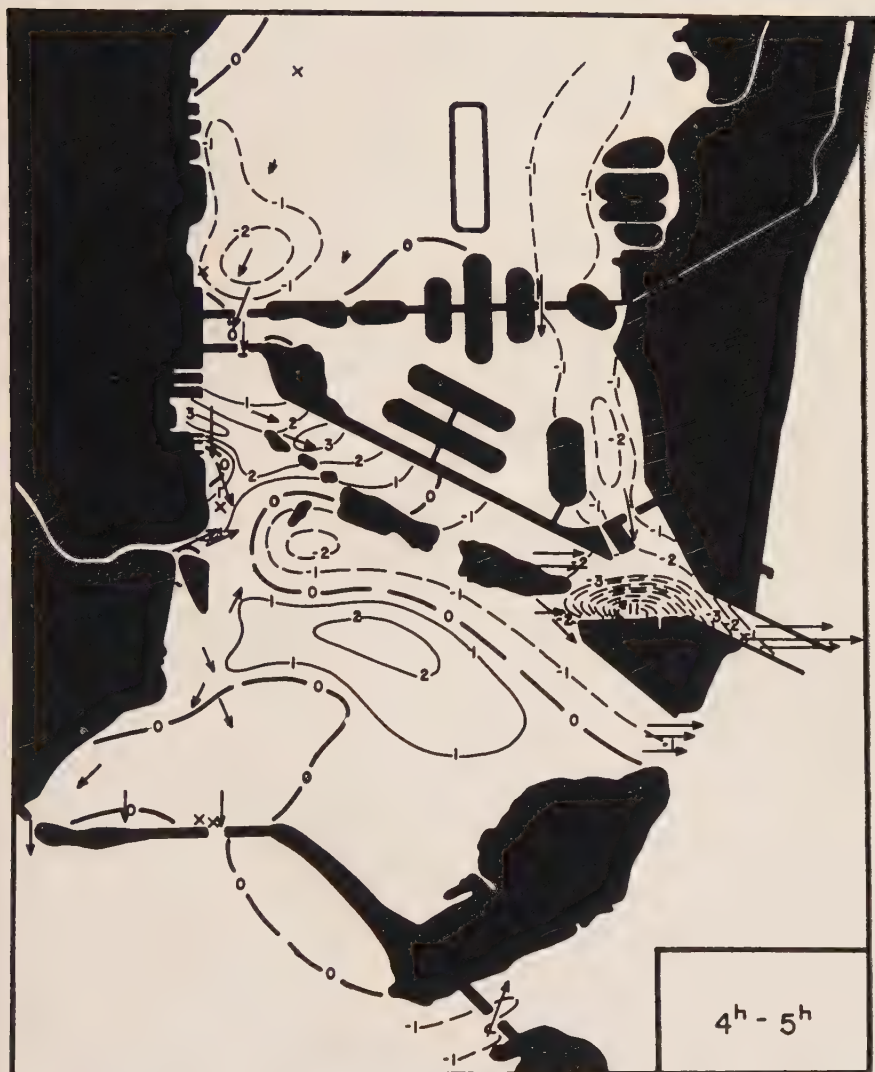


FIGURE 27. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

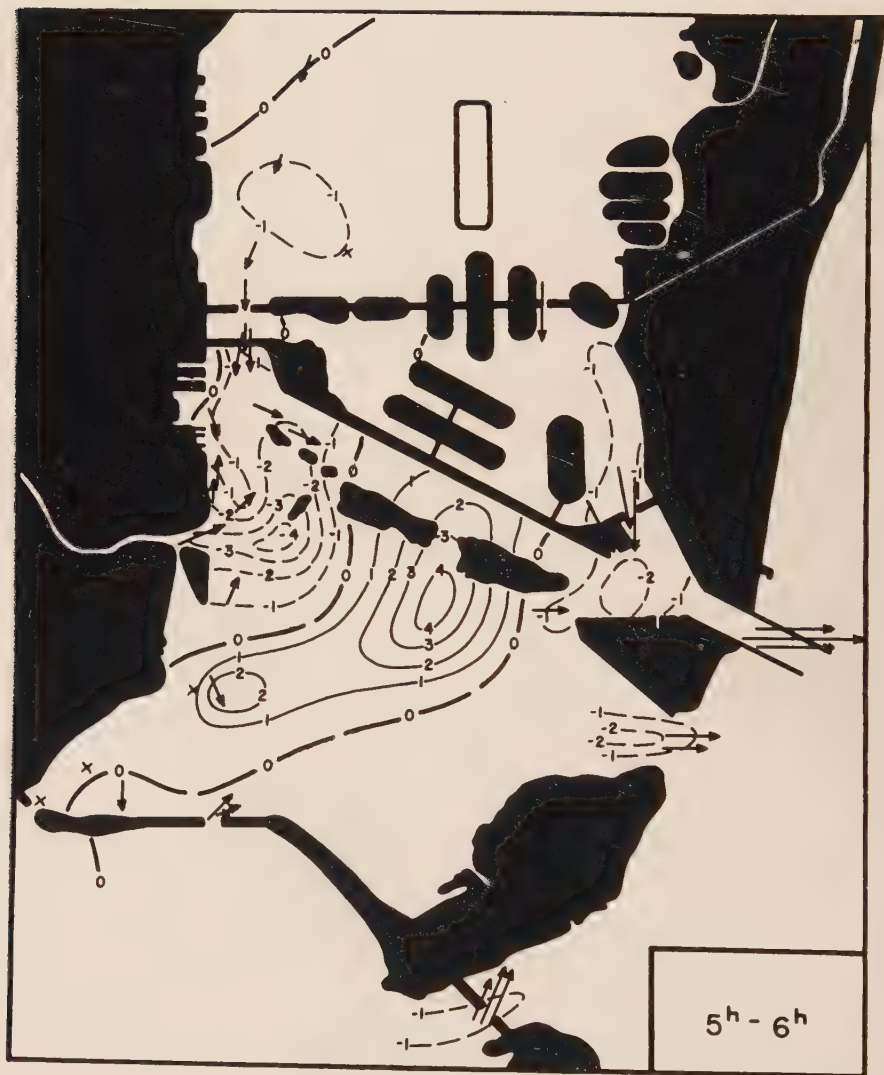


FIGURE 28. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

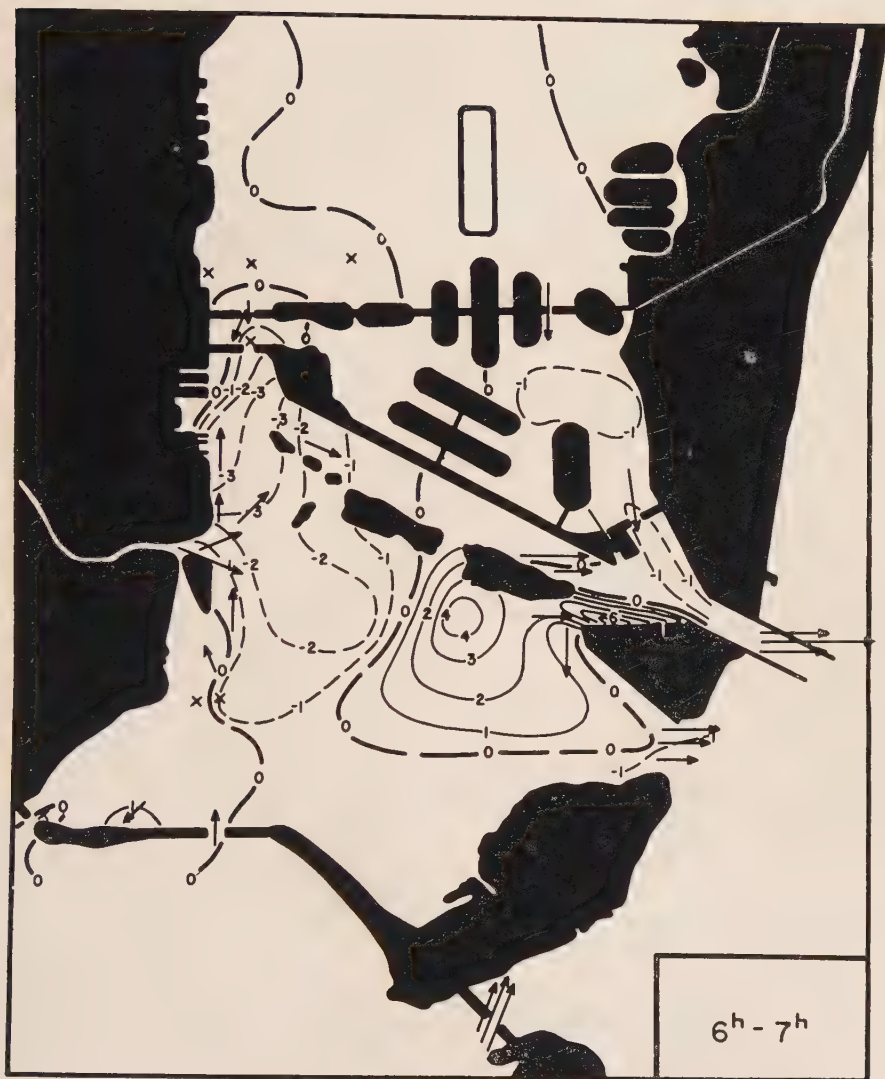


FIGURE 29. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

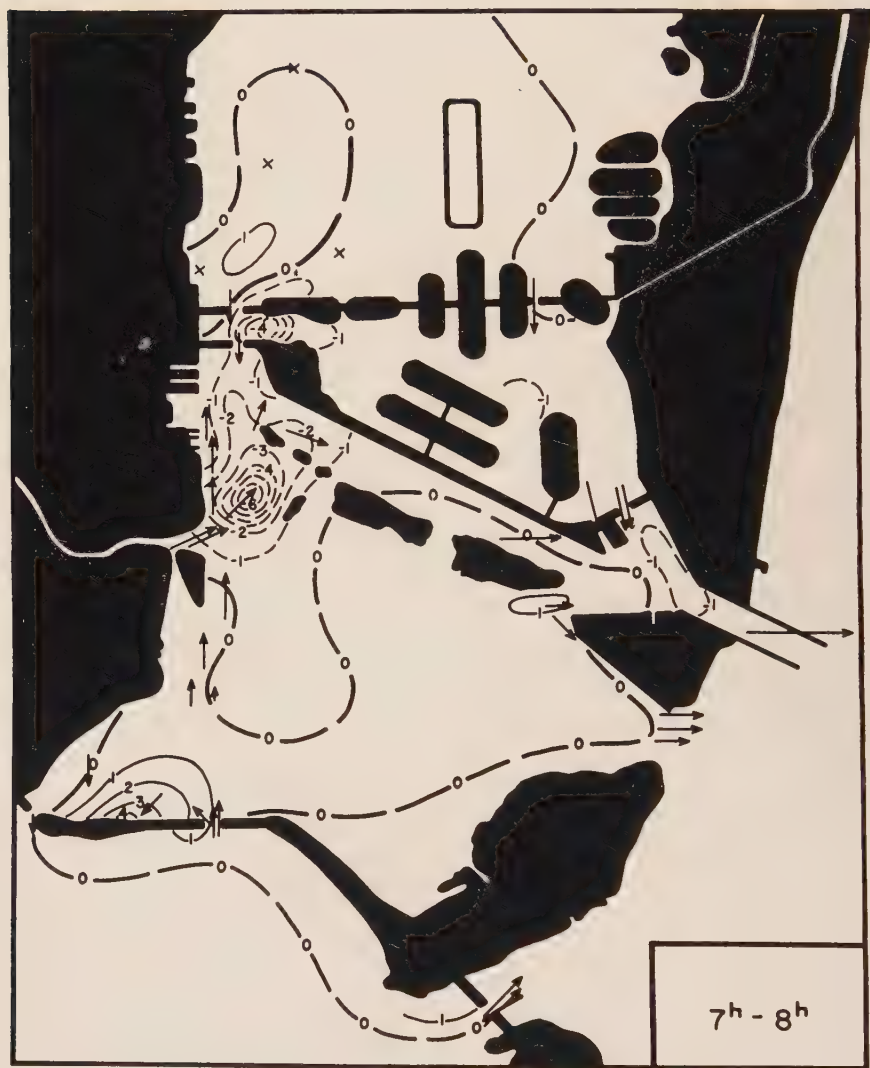


FIGURE 30. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.



FIGURE 31. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

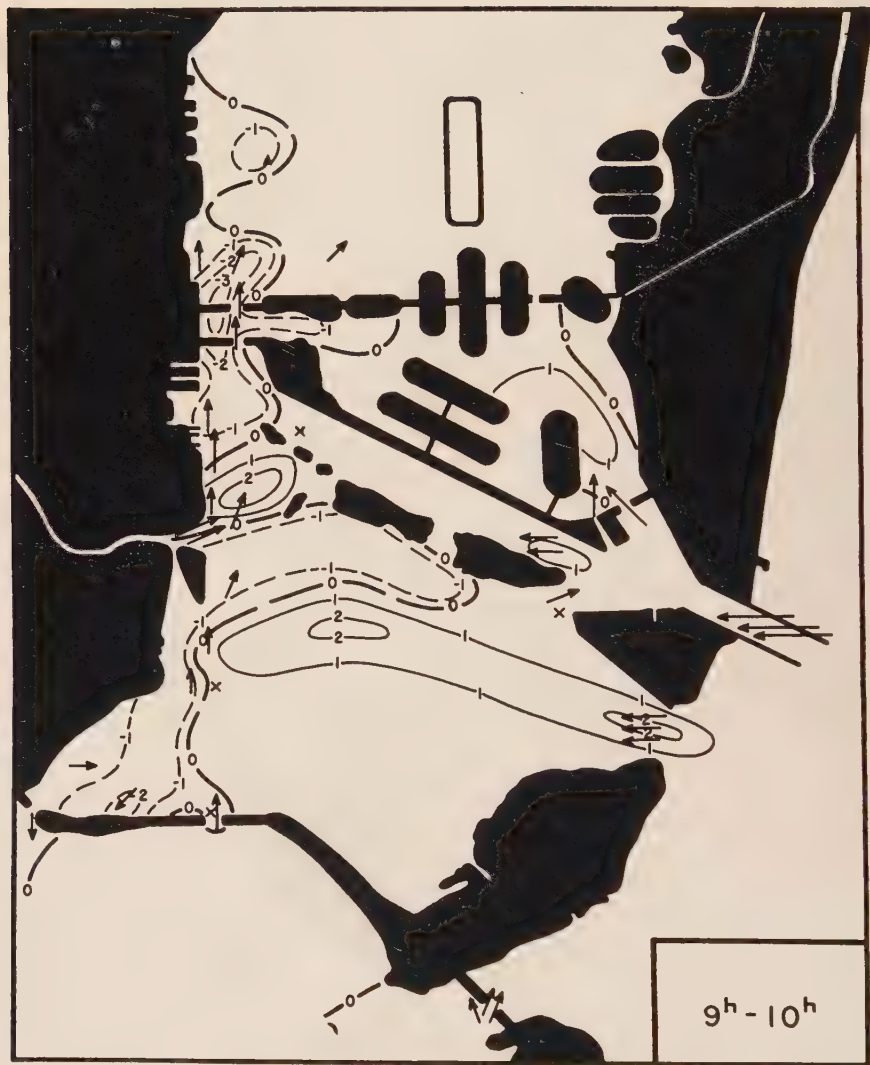


FIGURE 32. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

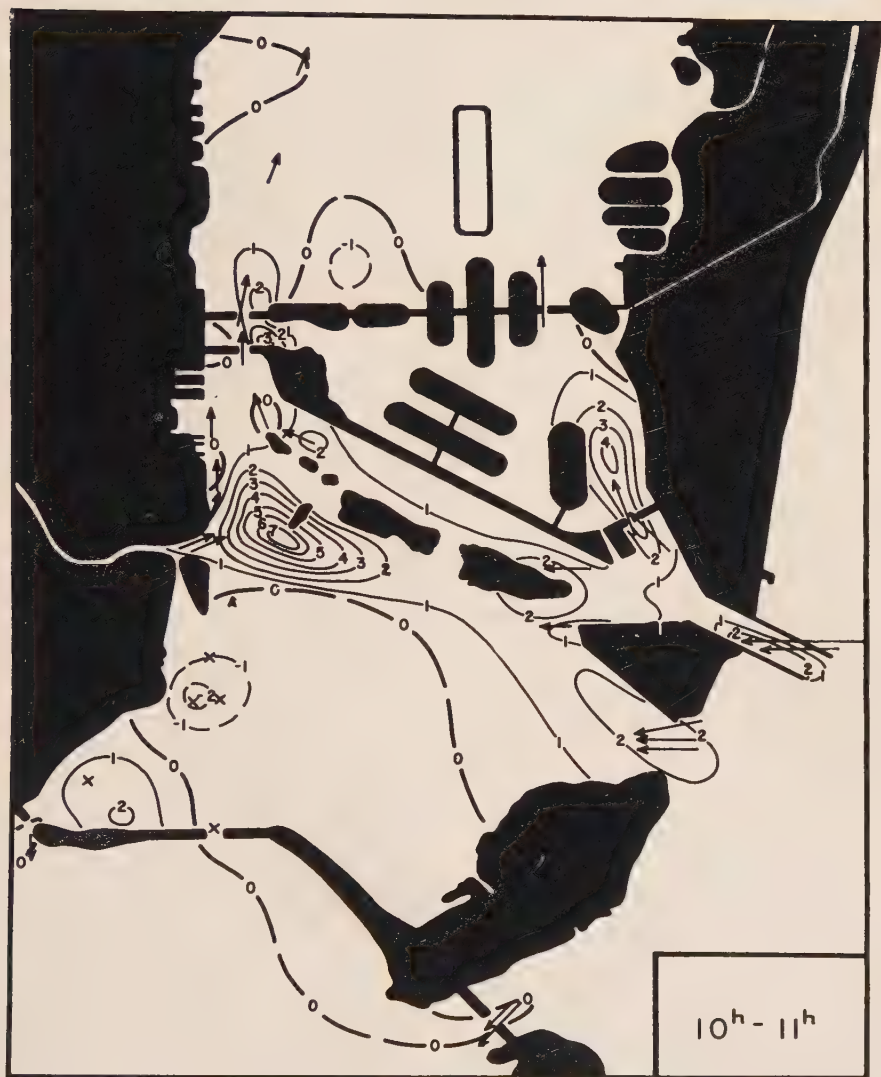


FIGURE 33. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

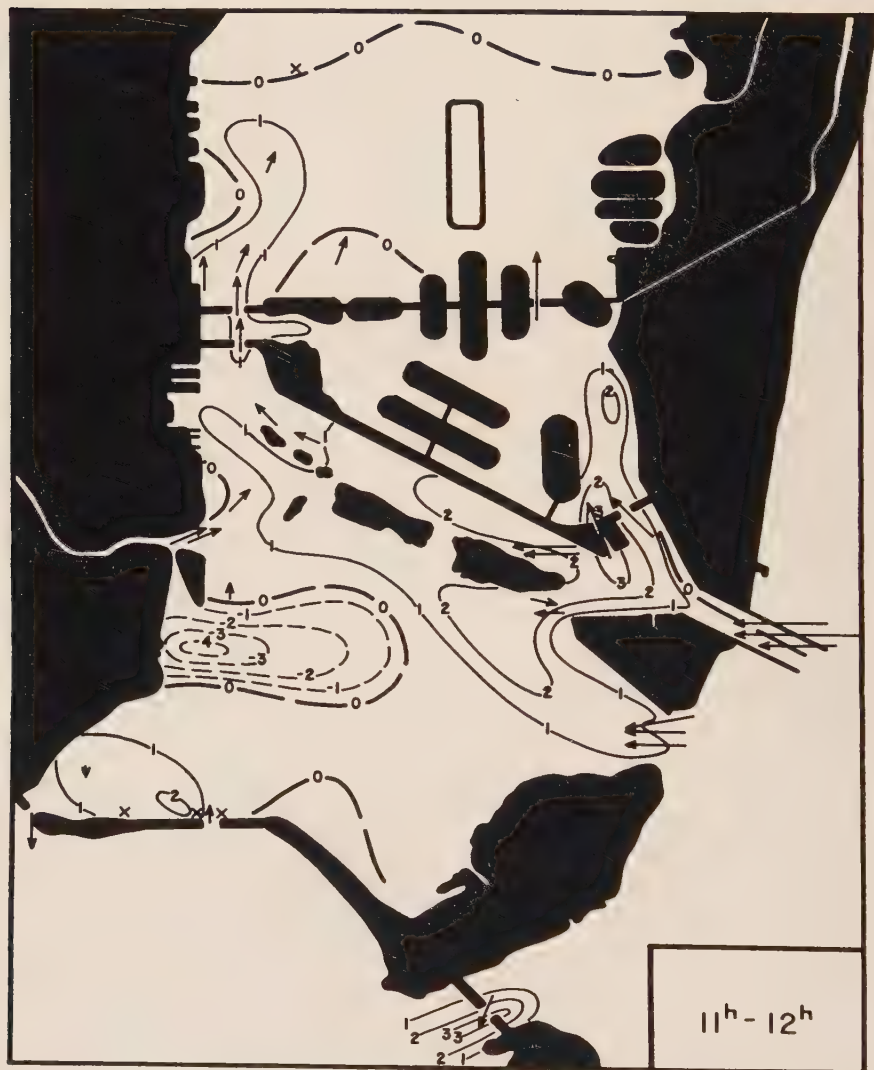


FIGURE 34. Horizontal distribution of the hourly changes in salinity, in parts per thousand; measured currents are indicated by arrows, the length of which shows the speed of current (1 cm or 0.39 inches corresponds to 1 knot). The hours are lunar. The time 0^h corresponds to the time when maximum flood is observed between the jetties of Government Cut. The x-signs refer to zero current.

magnitude observed. Lines or areas with no change in salinity in most cases seem to correspond to areas with no water movement (indicated by means of x-signs), although this is not necessarily always the case.

The increasing salinities are found at 0^h to 1^h in the whole area between the Government Cut, Norris Cut, and the western end of the Main Ship Channel. Correspondingly the currents run towards the west. Between 1^h and 2^h the increasing salinities are found in the area along the Dodge Islands, mainly in front of the Miami downtown area. Between 2^h and 3^h the increasing salinities are still found around the western bridges of MacArthur and Venetian Causeways.

The most pronounced local drops of salinity are found between the front of the mouth of Miami River at 2^h to 3^h o'clock and later, between 4^h and 5^h just north of Fisher Island.

The above waters are followed as ebbing current of more saline water. This water is seen at the western end of Main Ship Channel at 3^h to 4^h, in the central portion of the same Channel at 5^h to 6^h, and close to Fisher Island at 6^h to 7^h. The water movements in this area come to a standstill around 9^h.

After this period of time the less saline and heavily polluted waters from Government Cut are transported northwards along the shoreline of Miami Beach between 9^h and 12^h. The pronounced increase of salinity, south of the Dodge Islands, starts between 8^h and 9^h. However, it does not come to an end, as stated above, until before 3^h around the western bridges of the MacArthur and Venetian Causeways.

FLUSHING NUMBER

Arons and Stommel (1951) have shown that the relationship between the salinity distribution function S/σ and the dimensionless parameter $\lambda = X/L$ is exponential.

Where

$S = S(x)$ is the salinity in the estuary,
 σ is the salinity in the open ocean,
 L is the length of the (uniform) estuary,
 x -axis is directed positively downstream,
 F is the flushing number,

then,

$$\frac{S}{\sigma} = e^{F \left(1 - \frac{1}{\lambda}\right)}$$

The dimensionless parameter F is a convenient concept to characterize estuaries.

In dealing with Biscayne Bay, or actually with the flow between the main discharge of fresh water, Miami River, and the main tidal cut, Government Cut, the assumption of uniform width is not fulfilled. Nevertheless, even in this case with extreme non-uniformity of width, the above method gives a surprisingly clear-cut result (Figure 35). Although it is evident that the salinity curve for Biscayne Bay is sloping too much in the Miami River and in the Government Cut, and too slowly in the open Bay, the flushing number for Biscayne Bay can be estimated to be 0.3 or less.

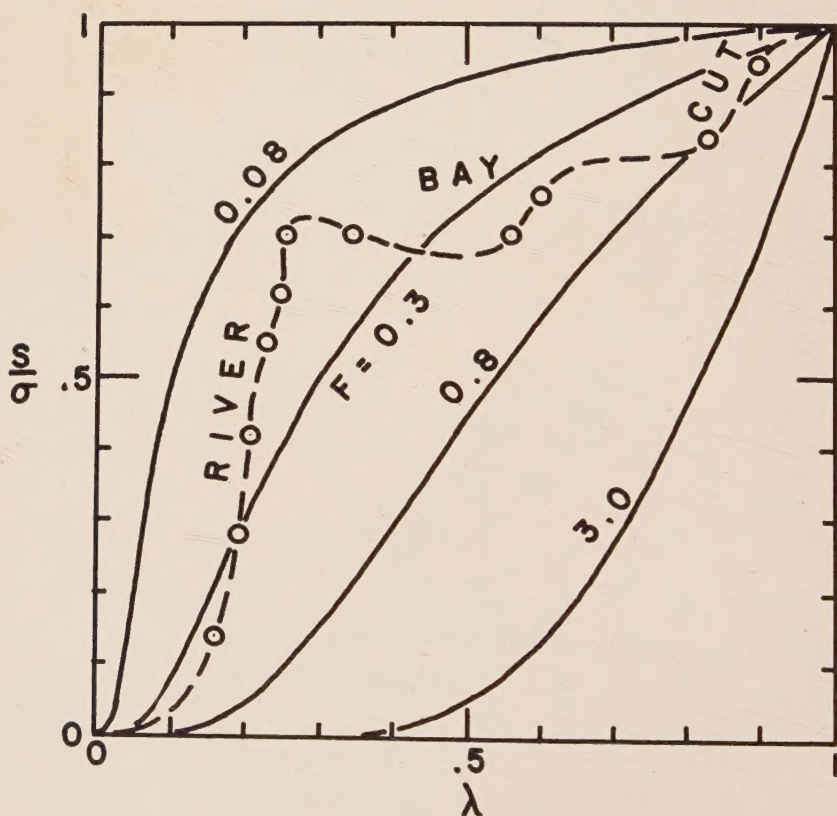


FIGURE 35. Determination of the flushing number for Biscayne Bay.

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